# ASTRONOMICAL INSTITUTE

## University of Utrecht

# ANNUAL REPORT

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# Chapter 1

# Astro plasma physics

Staff members: Prof.dr A. Achterberg, dr. J. Bergmans (postdoc), drs. J. Wiersma (PhD), B. van der Hoek (graduate)

## 1.1 Research

We specialize in the astrophysics of plasmas, which are gases consisting of charged particles.

Cosmic rays and high-energy astro particles

One of the main research interests of our group is the physics of Cosmic Rays These are highly energetic charged particles, which travel through space with speeds close to the speed of light. Some of these particles have tremendous amounts of energy. Especially the origin of these highest energy cosmic rays, the most energetic particles ever observed, is still unclear. Prof. Achterberg's research focuses on two theoretical aspects: the production and the propagation of Cosmic Rays.

We try to determine which production mechanisms could (in theory) accelerate these particles to such high energies, for example, in relativistic shock fronts. Because energetic cosmic rays travel almost with the speed of light, these particles could come from sources very far away: some of them have probably originated in other galaxies, and have been underway for millions of years. However, because they interact with the weak magnetic field that fills the intergalactic space, their propagation is not along a straight line, unlike light waves. We try to make predictions about the most probable origins of these Ultra High Energy Cosmic Rays.

This also involves thinking about other high-energy particles, in particular *neutrinos*. These neutrinos are very light particles that are produced as a by-product in sources where protons are accelerated to high energy. Very sensitive detectors are being built as we speak which could detect these elusive particles. Such a detection would allow us to take a close look inside the source, as neutrinos escape almost unhindered, and therefore carry information about the environment in which they were created.

Jorrit Wiersma works on a PhD project at the Astronomical Institute of Utrecht running from Feb 2001 to Feb 2006. Together with prof. Achterberg he studies the theory of shock waves moving close to the speed of light. Such shocks can occur in huge explosions (for example, the explosion of a very massive star at the end of its life) and might be the source of Gamma-ray Bursts coming from millions of lightyears away. We concentrate mainly on the theoretical role of magnetic fields in these shock waves. These magnetic fields play a crucial role in the mechanisms that produce the light that these shock waves emit, and may determine how the shock transition is formed. Unlike the shocks we are familiar with in every-day life, such as the sonic boom of an aircraft going through the sound barrier, these shocks are not the result of ordinary friction. The particle density is so low that collisions between individual particles play no role. Rather, waves and instabilities where a large group of particles acts collectively provide an effective frictional force which slows matter in a shock.
We solve the equations of plasma physics both analytically (on paper) and numerically (with computers) to predict the properties of the magnetic fields that we expect to find in such shock waves.

## 1.2 Academic publications

**Interaction of high-velocity pulsars with supernova remnant shells**
van der Swaluw, E.; Achterberg, A.; Gallant, Y. A.; Downes, T. P.; Keppens, R.
Astronomy and Astrophysics, v.397, p.913-920 (2003)

Hydrodynamical simulations are presented of a pulsar wind emitted by a supersonically moving pulsar. The pulsar moves through the interstellar medium or, in the more interesting case, through the supernova remnant created at its birth event. In both cases there exists a three-fold structure consisting of the wind termination shock, contact discontinuity and a bow shock bounding the pulsar wind nebula. Using hydrodynamical simulations we study the behaviour of the pulsar wind nebula inside a supernova remnant, and in particular the interaction with the outer shell of swept up interstellar matter and the blast wave surrounding the remnant. This interaction occurs when the pulsar breaks out of the supernova remnant. We assume the remnant is in the Sedov stage of its evolution. Just before break-through, the Mach number associated with the pulsar motion equals $M_{\rm psr} = \sqrt{7}5$, independent of the supernova explosion energy and pulsar velocity. The bow shock structure is shown to survive this break-through event.

# Chapter 2

# Magnetohydrodynamics of laboratory and astrophysical plasmas

Staff members: Prof.dr. J.P. Goedbloed

## 2.1 Research

The study of magnetohydrodynamics (MHD) of waves, instabilities, and supersonic flows of magnetized plasmas has been conducted for many years in the separate disciplines of laboratory fusion research and plasma-astrophysics. Yet, these widely separate physical situations are described by the same equations! This offers numerous common viewpoints for research of plasmas in the coronae of sun and stars, magnetospheres about planets and about pulsars, accretion disks about compact objects, the winds and jets ejected from them, etc. Since the early nineties, this starting point has been the basis of a multitude of collaborative efforts between FOM Rijnhuizen and the Utrecht Astronomy Department on Coronal plasma dynamics, Parallel Magneto-Fluid Dynamics, Rapid Changes in Complex Flows (with additional input from numerical mathematics, fluid dynamics, and physical informatics), and Magnetoseismology of accretion disks. At present, the studies of magnetized plasmas are continued with both linear (with an important analytical component) and nonlinear (numerical) techniques.

#### MHD spectroscopy and transonic MHD flows

The linear efforts concentrate on spectral analysis of MHD waves and instabilities: MHD spectroscopy has become a new powerful tool for plasma diagnostics (analogous to helioseismology) for different astrophysical systems (sunspots, coronal flux tubes, accretion disks, and jets). It has also led to a general set of state-of-the-art spectral codes for the analysis of MHD waves and instabilities for realistic laboratory experiments and astrophysical objects. The fundamental aspects of stationary MHD flows with transonic transitions through the critical MHD speeds proved to present many obstacles in understanding the subtleties of plasma dynamics. Having resolved those, permitted reinvestigating the MHD waves and instabilities of axisymmetric rotating plasmas with new numerical techniques. This activity is presently producing a veritable abundance of new instabilities of interest for the production of turbulence and angular momentum transport in accretion disks about compact objects.

### Nonlinear dynamics

The numerical effort concentrates on three-dimensional MHD modeling of laboratory plasma flows, stellar winds, astrophysical jets, and accretion flows, with coupling between the linear stability properties of the moving magnetized systems and the evolution towards discontinuous, shock-dominated, nonlinear dynamics. It exploits the Versatile Advection Code (VAC), developed by Gabor Tóth as part of the Massively Parallel Computing project mentioned above, which is a fully implicit, shock-capturing, and massively parallel MHD solver that bridges the huge time-scale disparities encountered in realistic astrophysical simulations. Designed to permit inclusion of almost all present discretization methods, it became an extremely versatile research instrument which is used by a rapidly increasing number of scientists, here and abroad. The code was steadily developed further by Rony Keppens (head of the Rijnhuizen Numerical Plasma Dynamics group), and applied to basic plasma dynamics like the Kelvin-Helmholtz instability and jets, solar and stellar winds (producing the anisotropy observed by the Ulysses spacecraft), and recently extended with adaptive mesh refinement and a relativistic module: another step towards simulating realistic astrophysical plasma flows.

### Teaching

The course on Magnetohydrodynamics of Astrophysical Plasmas has been transformed into a regular annual course, which is part of the masters curriculum.

## 2.2 Academic Publications

### Stability and waves of transonic laboratory and space plasmas

Goedbloed, J. P.

The properties of magnetohydrodynamic waves and instabilities of laboratory and space plasmas are determined by the overall magnetic confinement geometry and by the detailed distributions of the density, pressure, magnetic field, and background velocity of the plasma. Consequently, measurement of the spectrum of MHD waves (MHD spectroscopy) gives direct information on the internal state of the plasma, provided a theoretical model is available to solve the forward as well as the inverse spectral problems. This terminology entails a program, viz. to improve the accuracy of our knowledge of plasmas, both in the laboratory and in space. Here, helioseismology (which could be considered as one of the forms of MHD spectroscopy) may serve as a luminous example. The required study of magnetohydrodynamic waves and instabilities of both laboratory and space plasmas has been conducted for many years starting from the assumption of static equilibrium. Recently, there is a outburst of interest for plasma states where this assumption is violated. In fusion research, this interest is due to the importance of neutral beam heating and pumped divertor action for the extraction of heat and exhaust needed in future tokamak reactors. Both result in rotation of the plasma with speeds that do not permit the assumption of static equilibrium anymore. In astrophysics, observations in the full range of electromagnetic radiation has revealed the primary importance of plasma flows in such diverse situations as coronal flux tubes, stellar winds, rotating accretion disks, and jets emitted from radio galaxies. These flows have speeds which substantially influence the background stationary equilibrium state, if such a state exists at all. Consequently, it is important to study both the stationary states of magnetized plasmas with flow and the waves and instabilities they exhibit. We will present new results along these lines, extending from the discovery of gaps in the continuous spectrum and low-frequency Alfvn waves driven by rotation to the nonlinear flow patterns that occur when the background speed traverses the full range from sub-slow to super-fast.

**Computer simulations of solar plasmas**
Goedbloed, J. P.; Keppens, R.; Poedts, S.
Space Science Reviews, v. 107, Issue 1, p. 63-80 (2003).

Plasma dynamics has been investigated intensively for toroidal magnetic confinement in tokamaks with the aim to develop a controlled thermonuclear energy source. On the other hand, it is known that more than 90the discipline of plasma-astrophysics has an enormous scope. Magnetohydrodynamics (MHD) provides a common theoretical description of these two research areas where the hugely different scales do not play a role. It describes the interaction of electrically conducting fluids with magnetic fields that are, in turn, produced by the dynamics of the plasma itself. Since this theory is scale invariant with respect to lengths, times, and magnetic field strengths, for the nonlinear dynamics it makes no difference whether tokamaks, solar coronal magnetic loops, magnetospheres of neutron stars, or galactic plasmas are described. Important is the magnetic geometry determined by the magnetic field lines lying on magnetic surfaces where also the flows are concentrated. Yet, transfer of methods and results obtained in tokamak research to solar coronal plasma dynamics immediately runs into severe problems with trans'sonic' (surpassing any one of the three critical MHD speeds) stationary flows. For those flows, the standard paradigm for the analysis of waves and instabilities, viz. a split of the dynamics in equilibrium and perturbations, appears to break down. This problem is resolved by a detailed analysis of the singularities and discontinuities that appear in the trans'sonic' transitions, resulting in a unique characterization of the permissible flow regimes. It then becomes possible to initiate MHD spectroscopy of axi-symmetric transonic astrophysical plasmas, like accretion disks or solar magnetic loops, by computing the complete wave and instability spectra by means of the same methods (with unprecedented accuracy) exploited for tokamak plasmas. These large-scale linear programs are executed in tandem with the non-linear (shock-capturing, massively parallel) Versatile Advection Code to describe both the linear and the nonlinear phases of the instabilities.

# Chapter 3

# Stellar Winds, Outflowing Disks and Mass Loss

Staff members: Prof. H.J.G.L.M. Lamers, dr. M. Kraus (postdoc) drs. M. Fernandes (PhD)

## 3.1 Research

**Introduction**
During the last thirty years astronomers have discovered that nearly all stars are losing mass in the form of stellar winds through a major fraction of their lives. This mass loss affects their evolution from their origin to their death. It also leads to spectacular interactions between the supersonic stellar winds and the interstellar medium in the form of planetary nebulae and ring nebulae and in the form of interstellar bubbles and superbubbles. The return of matter from stars into the interstellar medium and the formation of bubbles and superbubbles changes the chemical composition of the galaxies and affects their kinematical properties.
Most types of stars eject mass in a spherically symmetric stellar wind. However several special types of stars eject their matter in the form of an equatorial disk. These are the rapid rotating Be-stars and the B[e] supergiant stars. Rotation plays a role in the formation of these outflowing disks. However centrifugal forces alone can not explain the observed properties, such as velocity, density and thickness.
Research in the Mdot group We study many aspects of stellar winds and outflowing disks, both observationally and theoretically. Most of these in collaboration with international colleagues.

## 3.2 Academic Publications

**The dynamics of the nebula M1-67 around the run-away Wolf-Rayet star WR 124**
van der Sluys, M. V.; Lamers, H. J. G. L. M.

Astronomy and Astrophysics, v.398, p.181-194

A new point of view on the dynamics of the circumstellar nebula M1-67 around the run-away Wolf-Rayet (WR) star WR 124 is presented. We simulated the outbursts of nebulae with different morphologies, to compare the results to the observed dynamical spectra of M1-67. We found that it has been interacting with the surrounding ISM and has formed a bow shock due to its high velocity of about 180 km $s^{-1}$ relative to the local ISM. The star is about 1.3 parsec away from the front of this bow shock. The outbursts that are responsible for the nebula are assumed to be discrete outbursts that occurred inside this bow shock. The ejecta collide with this bow shock shortly after the outburst. After the collision, they are dragged away by the pressure of the ISM, along the surface of the bow shock. The bow shock is oriented in such way that we are looking from the rear into this paraboloid, almost along the main axis. Evidence for this is given firstly by the fact that the far hemisphere is much brighter than the near hemisphere, secondly by the fact that there is hardly any emission found with radial velocities higher than the star's radial velocity, thirdly by the fact that the star looks to be in the centre of the nebula, as seen from Earth, and finally by the asymmetric overall velocity distribution of the nebula, which indicates higher radial velocities in the centre of the nebula, and lower velocities near the edges. We find evidence for at least two discrete outbursts that occurred inside this bow shock. For these outbursts, we find expansion velocities of $v_{\rm exp} \sim 150$ km $s^{-1}$ and dynamical timescales of about 0.8 and 2 $\times 10^4$ yr, which are typical values for LBV outbursts. We therefore conclude that M1-67 originates from several outbursts that occurred inside the bow shock around WR 124, during an LBV phase that preceded the current WR phase of the star.

**A quest for PMS candidate stars at low metallicity: Variable HAe/Be and Be stars in the Small Magellanic Cloud**

de Wit, W. J.; Beaulieu, J.-P.; Lamers, H. J. G. L. M.; Lesquoy, E.; Marquette, J.-B.

Astronomy and Astrophysics, v.410, p.199-216

We report the discovery of 5 new Herbig Ae/Be candidate stars in the Small Magellanic Cloud in addition to the 2 reported in Beaulieu et al. We discuss these 7 HAeBe candidate stars in terms of (1) their irregular photometric variability, (2) their near infrared emission, (3) their Halpha emission and (4) their spectral type. One star has the typical photometric behaviour that is observed only among Pre-Main Sequence UX Orionis type stars. The objects are more luminous than Galactic HAeBe stars and Large Magellanic Cloud HAeBe candidates of the same spectral type. The stars were discovered in a systematic search for variable stars in a subset of the EROS2 database consisting of 115 612 stars in a field of 24 $\times$ 24 arcmin in the Small Magellanic Cloud. In total we discovered 504 variable stars. After classifying the different objects according to their type of variability, we concentrate on 7 blue objects with irregular photometric behaviour. We cross-identified these objects with emission line catalogues from Simbad and JHK photometry from 2MASS. The analysis is supplemented with obtained narrow and broad band imaging. We discuss their variability in terms of dust obscuration and bound-free and free-free emission. We estimate the influence of metallicity on the circumstellar dust emission from pre-main sequence stars.

**Spectroscopic analysis of unclassified B[e] stars using forbidden lines**

Fernandes, M. B.; Kraus, M., De Araujo, F. X.; Lamers, H.

Boletim da Sociedade Astronmica Brasileira (ISSN 0101-3440), vol.23, no.1, p. 12-12

B[e] stars have a B type spectrum with forbidden lines in their optical spectrum. They form a very heterogeneous group with stars in different evolutionary stages. This group has pre-main sequence stars, supergiants, compact planetary nebulae, symbiotic objects and stars whose evolutionary stage is unknown, the unclassified B[e] stars. For this reason, it has been suggested, in the literature, the expression “Stars with the B[e] Phenomenon”. Intending to improve the discussion about the nature of some unclassified B[e] stars, we have analyzed high and low resolution spectra, obtained by us, with the FEROS and B&C spectrographs respectively, at the ESO 1.52m telescope in La Silla, Chile (agreement ESO/ON). First we have made a spectral atlas and after we have compared the observed luminosity of forbidden lines, specially [SII] lines, with luminosities predicted by a code written by us. This code derives the photoionization structure of a spherical and expanding wind with H, He and S. We are also considering the presence of an equatorial disk. Our main result is the mass loss rate () of the studied objects. This technique was already applied for the star Hen 2-90, where we have found a of $4 \times 10^{-8} M_{\odot}$ year$^{-1}$, considering a spherical wind and $7 \times 10^{-9} M_{\odot}$ year$^{-1}$, considering an equatorial disk. Both values indicate that this object is probably a compact planetary nebula showing the B[e] phenomenon (paper in preparation). We will show this conclusion, describing the code, and also the results for other unclassified B[e] stars of our sample, specially the stars MWC300 and CD-4211721.

**Ionization structure in the winds of B[e] supergiants. I. Ionization equilibrium calculations in a H plus He wind**

Kraus, M.; Lamers, H. J. G. L. M.

Astronomy and Astrophysics, v.405, p.165-174

The non-spherically symmetric winds of B[e] supergiants are investigated. An empirical density distribution is chosen that accounts for the density concentrations and ratios derived from observations, and our model winds are assumed to contain only hydrogen and helium. We first calculate the approximate ionization radii for H and He and compare the results with the ionization fractions calculated from the more accurate ionization balance equations. We find that winds with a $r^{-2}$ density distribution turn out to reach a constant ionization fraction as long as the wind density is low, i.e. in polar direction. For the high density equatorial regions, however, we find that the winds become neutral just above the stellar surface of the hot and massive B[e] supergiants forming a disk-like neutral region. In such a disk molecules and dust can form even very near the hot central star.

**Maximum mass-loss rates of line-driven winds of massive stars**
Aerts, C.; Lamers, H. J. G. L. M.
Astronomy and Astrophysics, v.403, p.625-635

We develop a theoretical treatment that allows us to determine the maximum mass-loss rate of a hot rotating star with a wind that is accelerated by radiation pressure due to spectral lines, taking into account finite disk correction as well as the effect of photon tiring but neglecting multiple scattering. The maximum mass-loss rate of a star is obtained by subsequent numerical integrations of the momentum equation from an assumed position of the sonic point onwards for increasing values of the mass loss, until the wind can no longer escape. For stars rotating below 80% of the critical velocity the decrease in the velocity far out in the wind due to the maximization of the mass loss is negligible. Stars rotating at >80% of the critical speed have a kinked velocity law connected with the highest possible mass-loss rate. In such cases the wind velocity increases up to typically a few stellar radii, and decreases subsequently almost ballistically outwards. In these cases the terminal wind velocity is much smaller than the maximum wind velocity. For O-type main-sequence stars, the maximum mass-loss rates derived from our formalism are somewhat smaller than those derived for self-regulated line-driven winds including multiple scattering. For B-type super giants, however, the maximum mass-loss rate is higher by about a factor 1.5-2. Including rotation, but without gravity darkening, results in a maximum mass-loss rate that is twice as high as for a non-rotating star.

**Massive Pre-Main Sequence Candidate Stars in the Small Magellanic Cloud**
de Wit, W. J.; Beaulieu, J.-P.; Lamers, H. J. G. L. M.; Brillant, S.
In Galactic Star Formation Across the Stellar Mass Spectrum, ASP Conference Series, Vol. 287, proceedings of the 2002 International Astronomical Observatories in Chile workshop, held 11-15 March 2002 at La Serena, Chile. Edited by James M. De Buizer and Nicole S. van der Bliek. San Francisco: Astronomical Society of the Pacific, ISBN: 1-58381-130-3, 2003, p. 198-203

We report the discovery of massive pre-main sequence candidate stars in the Small Magellanic Cloud. Among them we find one UXOri star. The stars are located in a region of enhanced 60 $\mu m$ emission. In comparison with Galactic and LMC Herbig Ae/Be stars of similar effective temperature, the

SMC objects seem to be more luminous. We discuss some of the difficulties in detecting PMS stars in a low metallicity environment, and we point out the importance of these stars in understanding the effect metallicity can have on the proto-stellar mass accretion rate.

**The evolutionary stage of five southern Galactic unclassified B[e] stars**

Borges Fernandes, Marcelo; de Araújo, Francisco X.; Lamers, H.

A Massive Star Odyssey: From Main Sequence to Supernova, Proceedings of IAU Symposium 212, held 24-28 June 2001 in Lanzarote, Canary island, Spain. Edited by Karel van der Hucht, Artemio Herrero, and Esteban, César. San Francisco: Astronomical Society of the Pacific, 2003, p.154

The spectra of stars with the B[e] phenomenon are dominated by features that are related to physical conditions of circumstellar material around these objects and are not intrinsic to the stars. Because of this, they form a very heterogeneous group. This group contains objects with different evolutionary stages. Lamers et al. (1998) have suggested a new designation with five sub-groups, which indicate the evolutionary stage. They are: supergiants, pre-main sequence or Herbig Ae/Be, compact planetary nebulae, symbiotic and unclassified. The unclassified group has many objects that need a better study to resolve their evolutionary status. Forbidden lines can be a useful tool to solve this problem. They can give informations about chemical composition, ionization and density of the circumstellar medium and probably the evolutionary phase of these objects. We analize spectra of some galactic objects, obtained with the FEROS and B&c spectrographs at the 1.52m telescope in ESO (La Silla-Chile), with a special focus on the forbidden lines. We have studied the spectra of five B[e] stars of uncertain evolutionary stage. We find that one of them is a pre-WN star, the other four are supergiant B[e] stars.

# Chapter 4

# Star clusters in Normal and Interacting Galaxies

Permanent staff: Prof. Henny J.G.L.M. Lamers (lamers@astro.uu.nl)
PhD students: Nate Bastian (bastian@astro.uu.nl), Mark Gieles (gieles@astro.uu.nl)
Master students: Johan Martens, Jacqueline Mout, Remco Scheepmaker

## 4.1 Research

Introduction Star clusters play a key role in the studies of the history of galaxies because they can be observed in galaxies up to distances of tens of millions of light years and because their age can be derived by standard methods from their photometry and spectrum. The age distribution of star clusters provides us with a record of the star formation history of galaxies. This is especially important when we want to understand what happens during (near) collisions or merging of galaxies.

Star clusters are destroyed by various internal and external effects. When a cluster loses so much mass that gravity cannot keep the stars together it dissolves into the field. Star clusters can be destroyed by internal effects, such as the loss of mass by stellar winds and supernova explosions, or by external effects, such as tidal effects of clusters in elliptical orbits, passing giant molecular clouds, density waves of spiral arms etc. The destruction time of star clusters depends on their initial mass and on the environment and is expected to be different in various galaxies. We expect the destruction time to be shortest in interacting or merging galaxies.

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## 4.2 Academic Publications

**Star cluster formation and evolution in nearby starburst galaxies - II. Initial conditions**

de Grijs, R.; Anders, P.; Bastian, N.; Lynds, R.; Lamers, H. J. G. L. M.; O'Neil, E. J.

Monthly Notice of the Royal Astronomical Society, Volume 343, Issue 4, pp. 1285-1300.

We use the ages, masses and metallicities of the rich young star cluster systems in the nearby starburst galaxies NGC 3310 and 6745 to derive their cluster formation histories and subsequent evolution. We further expand our analysis of the systematic uncertainties involved in the use of broadband observations to derive these parameters (Paper I) by examining the effects of a priori assumptions on the individual cluster metallicities. The age (and metallicity) distributions of both the clusters in the circumnuclear ring in NGC 3310 and of those outside the ring are statistically indistinguishable, but there is a clear and significant excess of higher-mass clusters in the ring compared to the non-ring cluster sample. It is likely that the physical conditions in the starburst ring may be conducive for the formation of higher-mass star clusters, on average, than in the relatively more quiescent environment of the main galactic disc. For the NGC6745 cluster system we derive a median age of ∼10 Myr. NGC6745 contains a significant population of high-mass 'super star clusters', with masses in the range $6.5 \lesssim \log(M_{\rm cl}/M_{\rm solar}) \lesssim 8.0$. This detection supports the scenario that such objects form preferentially in the extreme environments of interacting galaxies. The age of the cluster populations in both NGC3310 and 6745 is significantly lower than their respective characteristic cluster disruption time-scales, respectively $\log(t_4^{\rm dis}/yr) = 8.05$ and 7.75, for $10^4 M_{\rm solar}$ clusters. This allows us to obtain an independent estimate of the initial cluster mass function slope, $\alpha = 2.04(\pm 0.23) + 0.13 - 0.43$ for NGC3310, and $1.96(\pm 0.15) \pm 0.19$ for NGC6745, respectively, for masses $M_{\rm cl} \lesssim 10^5 M_{\rm solar}$ and $M_{\rm cl} \gtrsim 4 \times 10^5 M_{\rm solar}$. These mass function slopes are consistent with those of other young star cluster systems in interacting and star burst galaxies.

**Mapping the Galactic Halo. VI. Spectroscopic Measures of Luminosity and Metallicity**

Morrison, Heather L.; Norris, John; Mateo, Mario; Harding, Paul; Olszewski, Edward W.; Shectman, Stephen A.; Dohm-Palmer, R. C.; Helmi, Amina; Freeman, Kenneth C.

The Astronomical Journal, Volume 125, Issue 5, pp. 2502-2520.

We present our calibration of spectroscopic measures of luminosity and metallicity for halo giant candidates and give metallicities and distances for our first sample of spectroscopically confirmed giants. These giants have distances ranging from 15 to 83 kpc. As surveys reach farther into the Galaxy's halo with K giant samples, identification of giants becomes more difficult. This is because the numbers of foreground halo K dwarfs rise for V magnitudes of 19-20, typical for halo giants at $\sim 100$ kpc. Our photometric survey uses the strength of the Mg b/H feature near 5170 Å to weed K dwarfs out of the disk and thick disk, but we need spectroscopic measures of the strength of the Ca II K, Ca I $\lambda 4227$, and Mg b/H features to distinguish between the very metal-poor dwarfs and halo giants. Using a full error analysis of our spectroscopic measures, we show why a signal-to-noise ratio of $\sim 15$ pixel$^{-1}$ at Ca I $\lambda 4227$ and $\sim 10$ at Ca II K is needed for reliable luminosity discrimination. We use the Ca II K and Mg b features to measure metallicity in our halo giants, with typical errors (random plus systematic) of 0.3 dex for [Fe/H] values from -0.8 to -3.0.

**HST photometry of M51 cluster**

Bik, A.; Lamers, H. J. G. L. M.; Bastian, N.; Panagia, N.; Romaniello, M.

VizieR On-line Data Catalog: J/A+A/397/473. Originally published in: 2003A&A...397..473

M 51 was observed with HST-WFPC2 as part of the HST Supernova INtensive Study (SINS) program (Millard et al., 1999ApJ...527..746M). For this study we use the images taken in the broad band filters F336W (U), F439W (B), F555W (V), F675W (R) and F814W (I) from the SINS program and in the narrow band filters F502N ([OIII]) and F656N (H alpha) from the GO-program of H. C. Ford. The image in U was taken on 1994 May 12, the BVRI images were taken on Jan. 15 1995 and the [OIII] and H alpha images on Jan. 25 1995. The U and B images were split into three and two exposures of 400s and 700s respectively. The [OIII] and H alpha images are split into two exposures of 1200s and 500s ([OIII]) and 1400s and 400s (H alpha). In the remaining bands one single exposure of 600s was taken. The data was processed through the PODPS (Post Observing Data Processing System) for bias removal, flat fielding and dark frame correction.

**Star cluster formation and disruption time-scales - I. An empirical determination of the disruption time of star clusters in four galaxies**

Boutloukos, S. G.; Lamers, H. J. G. L. M.
Monthly Notice of the Royal Astronomical Society, Volume 338, Issue 3, pp. 717-732

We have derived the disruption times of star clusters from cluster samples of four galaxies, M51, M33, the Small Magellanic Cloud (SMC) and the solar neighbourhood. If the disruption time of clusters in a galaxy depends only on their initial mass as $t^{\mathrm{dis}}(yr) = t_4^{\mathrm{dis}}(M_{\mathrm{cl}}/10^4 M_{\mathrm{solar}})^{\gamma}$, and if the cluster formation rate is constant, then the mass and age distributions of the observed clusters will each be given by double power-law relations. For clusters of low mass or young age the power law depends on the fading of the clusters below the detection limit due to the evolution of the stars. For clusters of high mass and old age the power law depends on the disruption time of the clusters. The samples of clusters in M51 and M33, observed with HST-WFPC2, indeed show the predicted double power-law relations in both their mass and age distributions. The values of tdis4 and gamma can be derived from these relations. For the cluster samples of the SMC and the solar neighbourhood, taken from the literature, only the age distribution is known. This also shows the characteristic double power-law behaviour, which allows the determination of $t_4^{\mathrm{dis}}$ and gamma in these galaxies. The values of gamma are the same in the four galaxies within the uncertainty, and the mean value is $\gamma = 0.62 \pm 0.06$. However, the disruption time $t^4_{\mathrm{dis}}$ of a cluster of $10^4 M_{\mathrm{solar}}$ is very different in the different galaxies. The clusters in the SMC have the longest disruption time, $t_4^{\mathrm{dis}} \simeq 8 \times 10^9$ yr, and the clusters at 1-3 kpc from the nucleus of M51 have the shortest disruption time of $t_4^{\mathrm{dis}} \simeq 4 \times 10^7$ yr. The disruption time of clusters 1-5 kpc from the nucleus of M33 is $t_4^{\mathrm{dis}} \simeq 1.3 \times 10^8$ yr and for clusters within 1 kpc from the Sun we find $t_4^{\mathrm{dis}} \simeq 1.0 \times 10^9$ yr.

**Star cluster formation and disruption time-scales - II. Evolution of the star cluster system in the fossil starburst of M82**

de Grijs, Richard; Bastian, Nate; Lamers, Henny J. G. L. M.
Monthly Notice of the Royal Astronomical Society, Volume 340, Issue 1, pp. 197-209

We obtain new age and mass estimates for the star clusters in the fossil star burst region B of M82, based on improved fitting methods. Our new age estimates confirm the peak in the age histogram attributed to the last tidal encounter with M81; we find a peak formation epoch at slightly older ages than previously published, $\log(t_{\mathrm{peak}}\ \mathrm{yr}^{-1}) = 9.04$, with a Gaussian sigma of Delta $\log(t_{\mathrm{width}}) = 0.273$. The actual duration of the burst of cluster formation may have been shorter because uncertainties in the age determinations may have broadened the peak. Our improved mass estimates confirm that the (initial) masses of the M82 B clusters with $V \leqq 22.5$ mag are mostly in the range $10^4 - 10^6 M_{\mathrm{solar}}$, with a median mass of $M_{\mathrm{cl}} = 1.08 \times 10^5 M_{\mathrm{solar}}$. The formation history of the observed clusters shows a

steady decrease towards older ages. This indicates that cluster disruption has removed a large fraction of the older clusters. Adopting the expression for the cluster disruption time-scale of $t_{\rm dis}(M) = t_4^{\rm dis}(M/10^4 M_{\rm solar})\gamma$ with $\gamma \simeq 0.62$ (Paper I), we find that the ratios between the real cluster formation rates in the pre-burst phase [$\log(t\ {\rm yr}^{-1}) \geqq 9.4$], the burst phase [$8.4 < \log(t\ {\rm yr}^{-1}) < 9.4$] and the post-burst phase [$\log(t\ {\rm yr}^{-1}) \leqq 8.4$] are approximately . The formation rate during the burst may have been higher if the actual duration of the burst was shorter than adopted.
The mass distribution of the clusters formed during the burst shows a turnover at $\log(M_{\rm cl}/M_{\rm solar}) \simeq 5.3$ that is not caused by selection effects. This distribution can be explained by cluster formation with an initial power-law mass function of slope $\alpha = 2$ up to a maximum cluster mass of $M_{\rm max} = 3 \times 10^6 M_{\rm solar}$ and cluster disruption with a normalization time-scale $t_4^{\rm dis}/t_{\rm burst} = (3.0 \pm 0.3) \times 10^{-2}$. For a burst age of $1 \times 10^9$ yr, we find that the disruption time-scale of a cluster of $10^4 M_{\rm solar}$ is $t_4^{\rm dis} \sim 3 \times 10^7$ yr, with an uncertainty of approximately a factor of 2. This is the shortest disruption time-scale known in any (disc region of a) galaxy.

**The Missing Link in Star Cluster Evolution**
de Grijs, Richard; Bastian, Nate; Lamers, Henny J. G. L. M.
The Astrophysical Journal, Volume 583, Issue 1, pp. L17-L20

The currently most popular models for the dynamical evolution of star clusters predict that the power-law cluster luminosity functions (CLFs) of young star cluster systems will be transformed rapidly into the universal Gaussian CLFs of old Milky Way-type "globular" cluster systems. Here, we provide the first evidence for a turnover in the intermediate-age ∼ 1 Gyr old CLF in the center of the nearby star burst galaxy M82, which very closely matches the universal CLFs of old Milky Way-type globular cluster systems. Thiors provides an important test of both cluster disruption theories and hierarchical galaxy formation models. It also lends strong support to the scenario that these young cluster systems may eventually evolve into old Milky Way-type globular cluster systems. M82's proximity, its shortest known cluster disruption timescale of any galaxy, and its well-defined peak of cluster formation make it an ideal candidate to probe the evolution of its star cluster system to fainter luminosities, and thus lower masses, than has been possible for any galaxy before.

**Clusters in the inner spiral arms of M 51: The cluster IMF and the formation history**
Bik, A.; Lamers, H. J. G. L. M.; Bastian, N.; Panagia, N.; Romaniello, M.
Astronomy and Astrophysics, v.397, p.473-486

We present the results of an analysis of the HST-WFPC2 observations of the interacting galaxy M 51. From the observations in 5 broadband filters (UBVRI) and two narrow band filters (H alpha and [OIII]) we study the cluster population in a region of $3.2 \times 3.2$ kpc$^2$ in the inner spiral arms of M 51, at a distance of about 1 to 3 kpc from the nucleus. We found 877 cluster candidates and we derived their ages, initial masses and extinctions by means of a comparison between the observed spectral energy distribution and the predictions from cluster synthesis models for instantaneous star formation and solar metallicity. The lack of [OIII] emission in even the youngest clusters with strong H alpha emission, indicates the absence of the most massive stars and suggests a mass upper limit of about 25 to 30 $M_{sun}$. The mass versus age distribution of the clusters shows a drastic decrease in the number of clusters with age, much more severe than can be expected on the basis of evolutionary fading of the clusters. This indicates that cluster dispersion is occurring on a timescale of 10 Myr or longer. The cluster initial mass function has been derived from clusters younger than 10 Myr by a linear regression fit of the cumulative mass distribution. This results in an exponent $\alpha = -d\log N(M)/d\log(M) = 2.1 \pm 0.3$ in the range of $2.5 \times 10^3 < M < 5 \times 10^4 M_\odot$ but with an overabundance of clusters with $M > 2 \times 10^4 M_{\rm sun}$. In the restricted range of $2.5 \times 10^3 < M < 2 \times 10^4 M_{\rm sun}$ we find $\alpha = 2.0 \pm 0.05$. This exponent is very similar to the value derived for clusters in the interacting Antennae galaxies, and to the exponent of the mass distribution of the giant molecular clouds in our Galaxy. To study the possible effects of the interaction of M 51 with its companion NGC 5195 about 400 Myr ago, which triggered a huge star burst in the nucleus, we determined the cluster formation rate as a function of time for clusters with an initial mass larger than $10^4 M_{\rm sun}$. There is no evidence for a peak in the cluster formation rate at around 200 to 400 Myr ago within 2 sigma accuracy, i.e. within a factor two. The formation rate of the detected clusters decreases strongly with age by about a factor $10^2$ between 10 Myr and 1 Gyr. For clusters older than about 150 Myr this is due to the evolutionary fading of the clusters below the detection limit. For clusters younger than 100 Myr this is due to the dispersion of the clusters, unless one assumes that the cluster formation rate has been steadily increasing with time from 1 Gyr ago to the present time. Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. The coordinates and the photometry of the objects are available in electronic form at http://astro.uu.nl/ bastian/M51-bik/ and at http://www.edpsciences.org

**The Disruption Time of Clusters in Selected Regions of Four Galaxies**

Lamers, Henny J. G. L. M.; Boutloukos, Stratos G.

Extragalactic Globular Cluster Systems, Proceedings of the ESO Workshop held in Garching, Germany, 27-30 August 2002, p. 22.

If the cluster formation rate is constant and the disruption time of clusters depends on their initial mass as $t^{\rm dis} = t_4 \times (M_{\rm cl}/10^4 M_{\rm dot})^\gamma$, the values of $t_4$ and $\gamma$ can be derived in a very simple way from the age and mass histograms of large homogeneous samples of clusters with reliable age and/or mass determinations. We demonstrate the method and derive the values of $t_4$ and gamma from cluster samples in selected fields of four galaxies: M51, M33, SMC and the solar neighbourhood. The values of gamma are the same within their uncertainties in the four galaxies with $< \gamma >= 0.62 \pm 0.06$. However, the disruption time $t_4$ of clusters of $10^4 M_\odot$ is very different in the different locations. It is shortest in the inner region of M51 ($t_4 = 4 times 10^7$ yrs) and highest in the SMC ($t_4 = 4 times 10^9$ yrs).

**Selection of Metal-poor Giant Stars Using the Sloan Digital Sky Survey Photometric System**

Helmi, Amina; Ivezic, Zeljko; Prada, Francisco; Pentericci, Laura; Rockosi, Constance M.; Schneider, Donald P.; Grebel, Eva K.; Harbeck, Daniel; Lupton, Robert H.; Gunn, James E.; Knapp, Gillian R.; Strauss, Michael A.; Brinkmann, Jonathan

The Astrophysical Journal, Volume 586, Issue 1, pp. 195-200

We present a method for the photometric selection of metal-poor halo giants from the imaging data of the Sloan Digital Sky Survey[9] (SDSS). These stars are offset from the stellar locus in the g-r versus u-g color-color diagram. Based on a sample of 29 candidates for which spectra were taken, we derive a selection efficiency of the order of 50% for stars brighter than $r \sim 17$mag. The candidates selected in 400 $\deg^2$ of sky from the SDSS Early Data Release trace the known halo structures (tidal streams from the Sagittarius dwarf galaxy and the Draco dwarf spheroidal galaxy), indicating that such a color-selected sample can be used to study the halo structure even without spectroscopic information. This method, and supplemental techniques for selecting halo stars, such as RR Lyrae stars and other blue horizontal-branch stars, can produce an unprecedented three-dimensional map of the Galactic halo based on the SDSS imaging survey.

# Chapter 5

# Stellar evolution and Nucleosynthesis

Permanent staff: Norbert Langer, Onno Pols
Group members: Jasinta Dewi, Allard-Jan van Marle, Robert Nolet, Aarnout van Oosten, Jerome Petri, Jelena Petrovic, Arend Jan Poelarends, Marc van der Sluys, Sung-Chul Yoon
Former members: Hartmut Braun, Luc Dessart, Andreas Deutschmann, Jens Fliegner, Alexander Heger, Falk Herwig, Silvia Scheithauer, Stephan Wellstein

## 5.1 Research

General field: structure and evolution of single and binary stars, nucleosynthesis, stellar winds, binary mass transfer and accretion, formation and evolution of circumstellar and circumbinary nebulae, formation of white dwarfs, neutron stars, black holes, supernovae and gamma-ray bursts.
Hot open questions: What are the effects of rotation on stellar evolution, nucleosynthesis, and circumstellar nebulae? Which binary systems can produce black holes, which gamma-ray bursts? What are the progenitors of Type Ia Supernovae? Which stars synthesise the r-process elements? Which processes can drive mass out of binary systems? What shapes circumstellar nebulae and supernova remnants?

Possible research project and thesis work: Research work in our group is mostly theoretical and fundamental, but always strongly linked to observations. We try to be at the forefront of research and to produce new, relevant publishable results which will be interesting to a large community of astrophysicists. Small Research Projects and work leading to a Master Thesis can be started any time, PhD work on request.

## 5.2 Academic Publications

**The first binary star evolution model producing a Chandrasekhar mass white dwarf**

Yoon, S.-C.; Langer, N.

Astronomy and Astrophysics, v.412, p.L53-L56

Today, Type Ia supernovae are essential tools for cosmology, and recognized as major contributors to the chemical evolution of galaxies. The construction of detailed supernova progenitor models, however, was so far prevented by various physical and numerical difficulties in simulating binary systems with an accreting white dwarf component, e.g., unstable helium shell burning which may cause significant expansion and mass loss. Here, we present the first binary evolution calculation which models both stellar components and the binary interaction simultaneously, and where the white dwarf mass grows up to the Chandrasekhar limit by mass accretion. Our model starts with a $1.6M_{\rm sun}$ helium star and a $1.0M_{\rm sun}$ CO white dwarf in a 0.124 day orbit. Thermally unstable mass transfer starts when the CO core of the helium star reaches $0.53M_{\rm sun}$, with mass transfer rates of $1 * s8 \times 10^{-6} M_{\rm sun}/{\rm yr}$. The white dwarf burns the accreted helium steadily until the white dwarf mass has reached $\sim 1.3M_{\rm sun}$ and weak thermal pulses follow until carbon ignites in the center when the white dwarf reaches $1.37M_{\rm sun}$. Although the supernova production rate through this channel is not well known, and this channel can not be the only one as its progenitor life time is rather short ( $\sim 10^7 - 10^8$ yr), our results indicate that helium star plus white dwarf systems form a reliable route for producing Type Ia supernovae.

**The s-Process in Rotating Asymptotic Giant Branch Stars**

Herwig, Falk; Langer, Norbert; Lugaro, Maria

The Astrophysical Journal, Volume 593, Issue 2, pp. 1056-1073

We model the nucleosynthesis during the thermal pulse phase of a rotating, solar metallicity, asymptotic giant branch (AGB) star of 3 $M_{\rm solar}$, which was evolved from a main-sequence model rotating with 250 km $s^{-1}$ at the stellar equator. Rotationally induced mixing during the thermal pulses produces a layer ($\sim 2 \times 10^{-5} M_{\rm solar}$) on top of the CO core where large amounts of protons and $^{12}$C coexist. With a postprocessing nucleosynthesis and mixing code, we follow the abundance evolution in this layer, in particular that of the neutron source $^{13}$C and of the neutron poison $^{14}$N. In our AGB model mixing persists during the entire interpulse phase because of the steep angular velocity gradient at the core-envelope interface, thereby spreading $^{14}$N over the entire $^{13}$C-rich part of the layer. We follow the neutron production during the interpulse phase and find a resulting maximum neutron exposure of $\tau_{\rm max} = 0.04 mbarn^{-1}$, which is too small to produce any significant s-process. In parametric models, we then investigate the combined effects of diffusive overshooting from the convective envelope and rotationally induced mixing. Just adding the overshooting and leaving the rotational mixing unchanged results in a small maximum neutron exposure (0.03 mbarn-1). Models with overshoot and weaker interpulse mixing-as perhaps expected from more slowly rotating stars-yield larger neutron exposures. In a model with overshooting without any interpulse mixing a neutron exposure of up to 0.72 $mbarn^{-1}$ is obtained, which is larger than required by observations. We conclude that the incorporation of rotationally induced mixing processes has important consequences for the production of heavy elements in AGB stars. While through a distribution of initial rotation rates, it may lead to a natural spread in the neutron exposures obtained in AGB stars of a given mass in general - as appears to be required by observations - it may moderate the large neutron exposures found in models with diffusive overshoot in particular. Our results suggest that both processes, diffusive overshoot and rotational mixing, may be required to obtain a consistent description of the s-process in AGB stars that fulfills all observational constraints. Finally, we find that mixing due to rotation within our current framework does increase the production of $^{15}N$ in the partial mixing zone. However, this increase is not large enough to boost the production of fluorine to the level required by observations.

**How Massive Single Stars End Their Life**
Heger, A.; Fryer, C. L.; Woosley, S. E.; Langer, N.; Hartmann, D. H.
The Astrophysical Journal, Volume 591, Issue 1, pp. 288-300

How massive stars die-what sort of explosion and remnant each produces-depends chiefly on the masses of their helium cores and hydrogen envelopes at death. For single stars, stellar winds are the only means of mass loss, and these are a function of the metallicity of the star. We discuss how metallicity, and a simplified prescription for its effect on mass loss, affects the evolution and final fate of massive stars. We map, as a function of mass and metallicity, where black holes and neutron stars are likely to form and where different types of supernovae are produced. Integrating over an initial mass function, we derive the relative populations as a function of metallicity. Provided that single stars rotate rapidly enough at death, we speculate on stellar populations that might produce gamma-ray bursts and jet-driven supernovae.

**The impact of radiation and wind momenta on mass transfer in massive close binary systems**
Dessart, L.; Langer, N.; Petrovic, J.
Astronomy and Astrophysics, v.404, p.991-996 (2003)

We investigate to what extent the radiation and stellar wind momenta in a massive close binary system can remove part of the matter flowing from one towards the other star during a mass transfer phase. We perform radiation-hydrodynamics simulations in the co-rotating frame of a binary system made-up of two main sequence stars of 27 $M_{sun}$ and 26 $M_{sun}$ in a 4 day orbit. We study the interaction of the winds of both stars, and of their photons, with the accretion stream originating from the Roche-lobe filling component. For our simulation, we adopt a mass transfer rate of $5 \times 10^{-6} M_{sun}$yr, a mid-point in the range of values during massive binary star evolution. Our simulations show that even for such moderate mass transfer rates, the wind and radiative momenta do not alter the dynamics of the accretion stream which is observed to follow essentially ballistic trajectories. Such a conclusion is reinforced for higher mass transfer rates because of the increased stream density and the correspondingly reduced radiation force. We anticipate that the radiation and wind momenta will affect the accretion stream only when its density is comparable to the wind's, a situation wherein the mass transfer rate is vanishingly small and irrelevant for binary star evolution. Alternatively, such reduced accretion stream density could be obtained from spatial dilution in wider systems, potentially leading to non-conservative mass transfer.

**Massive Star Evolution Through the Ages**
Heger, A.; Woosley, S. E.; Fryer, C. L.; Langer, N.
From Twilight to Highlight: The Physics of Supernovae. Proceedings of the ESO/MPA/MPE Workshop held in Garching, Germany, 29-31 July 2002, p. 3.

We review the current basic picture of the evolution of massive stars and how their evolution and structure changes as a function of initial mass. We give an overview of the fate of modern (Pop I) and primordial (Pop III) stars with emphasis on massive and very massive stars. For single stars we show how the type of explosions, the type of remnant and their frequencies changes for different initial metallicities.

**Evolution of Rotating AGB Stars and the s-Process Nucleosynthesis**
Siess, Lionel; Goriely, Stéphane; Langer, Norbert
Publications of the Astronomical Society of Australia, Volume 20, Issue 4, pp. 371-377.

We present new results on the evolution and nucleosynthesis in rotating AGB stars. We analyse the role of the gradient of mean molecular weight in the mixing process and show that neglecting this component induces a potentially strong third dredge-up. We also quantify the impact of rotation on the structure and conclude that the effects of rotation (1) mainly concern the inner, fast rotating regions of the stars and (2) are relatively weak as long as rotational mixing does not induce a deep third dredge-up. We also focus our investigations on the s-process nucleosynthesis and show that rotational mixing tends to inhibit the production of s-elements. This results from the contamination of the $^{13}$C-rich layers responsible for the neutron production by the poisonous $^{14}$N. Our calculations also indicate that the distribution of s-process elements depends sensitively on the magnitude of the diffusion coefficient. These results suggest that rotational mixing is not the main mechanism responsible for the production of s-elements in AGB stars, but that it can influence, and in particular reduce, the final enrichment in s-elements.

**Progenitor models of Wolf-Rayet binaries: short-period WNE+O binaries with mass ratios q $\simeq$ 0.5**
Petrovic, Jelena; Langer, Norbert
A Massive Star Odyssey: From Main Sequence to Supernova, Proceedings of IAU Symposium 212, held 24-28 June 2001 in Lanzarote, Canary island, Spain. Edited by Karel van der Hucht, Artemio Herrero, and Esteban, César. San Francisco: Astronomical Society of the Pacific, 2003, p.418

We identify two possible paths for the progenitor evolution of observed WNE+O binaries with WNE/O mass ratios close to 0.5 and periods between 7 and 10 d. We show, through detailed binary evolution models, that with the assumption that the O-type star expels most of the matter flowing at it during mass transfer, one possibility to obtain the observed systems is through Case A mass transfer. We find a second solution using standard common envelope evolution. We conclude that in either case the O-type star in the three investigated systems did not accrete significant amounts of mass. We discuss the intricate situation that in other cases massive close binaries may evolve conservatively.

**Influence of radiation pressure and wind momentum on mass transfer in massive binaries**
Dessart, Luc; Petrovic, Jelena; Langer, Norbert
A Massive Star Odyssey: From Main Sequence to Supernova, Proceedings of IAU Symposium 212, held 24-28 June 2001 in Lanzarote, Canary island, Spain. Edited by Karel van der Hucht, Artemio Herrero, and Esteban, César. San Francisco: Astronomical Society of the Pacific, 2003, p.408

We perform radiation hydrodynamics simulations of mass transfer in close and massive binary systems, focusing especially on the impact of radiation pressure and wind momentum from the two luminous stars that compose the system. We find that for the large mass transfer rates important for the evolution of such binary systems (of the order of $10^{-3} M_{\odot}$; yr$^{-1}$), the light and wind momenta are too low to affect the behaviour of the dense gas stream ejected by the Roche Lobe filling component. In particular, the presence of a wind-wind collision between the two stars has no effect on the gas stream dynamics.

**On the evolution of massive close binaries**
Langer, N.; Wellstein, S.; Petrovic, J.

A Massive Star Odyssey: From Main Sequence to Supernova, Proceedings of IAU Symposium 212, held 24-28 June 2001 in Lanzarote, Canary island, Spain. Edited by Karel van der Hucht, Artemio Herrero, and Esteban, César. San Francisco: Astronomical Society of the Pacific, 2003, p.275

We discuss which fraction of the matter flowing to the companion during a Roche lobe overflow phase can actually be accreted by the secondary star. Employing new evolutionary models for massive close binaries which include the effects of rotation for both components as well as angular momentum accretion and spin-orbit coupling, we propose a physical model to calculate the accretion efficiency in Case A and B systems. We provide examples showing that both cases, high and low accretion efficiency, do occur within these models, as it seems required by observed post-mass transfer systems. Furthermore, we discuss late evolutionary stages of such binaries, with emphasis on the formation of compact objects: what are their spin rates, which systems can produce black holes, which gamma-ray bursts?

**The pre-supernova evolution of rotating massive stars**

Heger, Alexander; Woosley, Stan E.; Langer, Norbert

A Massive Star Odyssey: From Main Sequence to Supernova, Proceedings of IAU Symposium 212, held 24-28 June 2001 in Lanzarote, Canary island, Spain. Edited by Karel van der Hucht, Artemio Herrero, and Esteban, César. San Francisco: Astronomical Society of the Pacific, 2003, p.357

Massive stars are born rotating rigidly with a significant fraction of critical rotation at the surface. Consequently, rotationally-induced circulation and instabilities lead to chemical mixing in regions that would otherwise be stable, as well as a redistribution of angular momentum. Differential rotation also winds up magnetic fields, causing instabilities that can power a dynamo and magnetic stresses that lead to additional angular momentum transport. We follow the evolution of typical massive stars, their structure and angular momentum distribution, from the zero-age main sequence until iron core collapse. Without the action of magnetic fields, the resulting angular momentum is sufficiently large to significantly affect the explosion mechanism and neutron star formation. Sub-millisecond pulsars result that could encounter the r-mode instability. In helium cores massive enough, at least at low metalicity, the angular momentum is also sufficiently great to form a centrifugally supported accretion disk around a central black hole, powering the engine of the 'collapsar' model for GRBs. Including current estimates of the effect of magnetic fields still allows the formation of rapidly rotating ($\sim 5--10$ ms) pulsars, but might leave too little angular momentum for collapsars.

# Chapter 6

# Solar Physics

Prof.dr. Rob Rutten - solar physics, DOT student observing
Dr. Ir. Rob Hammerschlag - DOT instrumentation
Ir. Felix Bettonvil - DOT instrumentation, observing campaigns
Dr. Pit Sütterlin - solar physics, DOT observing, speckle processing
Dr. Kostas Tziotziou - solar physics
Drs. Alfred de Wijn - solar physics, speckle processing
Drs. Jorrit Leenaarts - solar physics

## 6.1 Research

Solar physics research projects Most astronomical research of the solar physics group at the Sterrekundig Instituut Utrecht exploits its ownership of the Dutch Open Telescope (DOT) on La Palma, built and operated by our group.
Our group welcomes astronomy and physics students at Utrecht University or from other universities for Astrovaria (7.5 ects), Bachelor (15 ects) and Masters (60 ects) research projects. The project content may vary widely, from purely instrumentational to purely theoretical, but most of our projects involve image-sequence analysis and interpretation using the IDL language. Student research in our group often includes work abroad. Hands-on participation in DOT observing at La Palma will be offered increasingly, for example as the first part of an Astrovaria project.
Specific research topics on our list are:
solar wave dynamics: network and internetwork oscillations, gravity waves, umbral flashes, wave excitation;
solar surface fields: fluxtube patterns, fluxtube dynamics, magnetic carpet topology and evolution, sunspot structure and dynamics, prominence stability and eruptions;
topology and evolution of solar active regions: plage emergence and disappearance, eruption precursor topology, sunspot breakup;
solar canopy transitions: wave penetration and heating, moss structure and dynamics, spicule physics, tube-loop coupling. Most of the above can ex-

ploit DOT data. The DOT is an innovative solar telescope equipped with a multi-camera imaging system that in combination with speckle reconstruction delivers long image sequences that are often sharp down to the diffraction limit of 0.2 arcsec defined by the diameter of the primary mirror. The DOT produces such high-resolution image sequences simultaneously at different wavelengths which sample the solar atmosphere at different heights. There are beautiful examples on the DOT website.

With this tomographic imaging system, the DOT excels in mapping the topology, dynamics, and evolution of the enigmatic magnetic structures in the solar atmosphere such as filaments, sunspots, pores, and the tiny magnetic elements that make up plage and network and even occur in the quiet-sun internetwork. We exploit this capability in our research, often in collaboration with colleagues elsewhere. We also perform detailed comparisons with numerical simulations in order to identify the underlying physics.

The coming years will see much science harvesting of the unique DOT capabilities. A new advanced multi-processor speckle computer enables us to frequently participate in international observing campaigns, combining the DOT with other telescopes in the Canary Islands and with EUV and X-ray telescopes in space. The aim is to diagnose solar magnetism from the deep photosphere out to the corona. The DOT will be a major player in these multi-telescope campaigns. You are welcome to share in these exciting prospects.

Definition of an appropriate student research topic is best reached through discussion - come talk!

## 6.2 Academic Publications

**Dynamics of the solar chromosphere IV. Evidence for atmospheric gravity waves from TRACE**

Rutten, R. J.; Krijger, J. M.

Astronomy and Astrophysics, v.407, p.735-740

We study the low-frequency brightness modulation of internetwork regions in the low solar chromosphere using simultaneous ultraviolet and white-light image sequences from the Transition Region and Coronal Explorer (TRACE). The ultraviolet sequences exhibit a slowly varying brightness pattern in internetwork regions on which the more familiar acoustic three-minute oscillation is superimposed, with about half of the peak brightness reached in internetwork grains contributed by the low-frequency background. We address the nature of the latter, applying two-dimensional Fourier filtering to isolate it from the acoustic modulation. Spatio-temporal comparisons and selective time-delay scatter correlations between the ultraviolet and white-light low-frequency sequences establish that reversed granulation constitutes at most a minor part of the ultraviolet background. Fourier analysis shows that the meso-scale contribution dominates and consists of atmospheric gravity waves.

**The Dutch Open Telescope**
Rutten, Robert J.
The Future of Small Telescopes In The New Millennium. Volume II - The Telescopes We Use. Edited by Terry D. Oswalt. Astrophysics and Space Science Library, Volume 288, Kluwer Academic Publishers, Dordrecht, 2003, p.111
Book

**La Palma observations of umbral flashes**
Rouppe van der Voort, L. H. M.; Rutten, R. J.; Sütterlin, P.; Sloover, P. J.; Krijger, J. M.
Astronomy and Astrophysics, v.403, p.277-285 (2003)

We present high-quality Ca II H and K data showing chromospheric flashes in sunspot umbrae collected with the Swedish Vacuum Solar Telescope, the Dutch Open Telescope, and the Swedish 1-m Solar Telescope at the Roque de los Muchachos Observatory on La Palma. Differential movies, time slices, spectrograms, and Fourier power maps demonstrate that umbral flashes and running penumbral waves are closely related oscillatory phenomena, combining upward shock propagation with coherent wave spreading over the entire spot. We attribute the flash brightening to large redshift by post-shock material higher up. We find no obvious relation between umbral dots and umbral flashes.

**Multi-wavelength imaging system for the Dutch Open Telescope**
Bettonvil, Felix C.; Sütterlin, Peter; Hammerschlag, Robert H.; Jaegers, Aswin P.; Rutten, Robert J.
Innovative Telescopes and Instrumentation for Solar Astrophysics. Edited by Stephen L. Keil, Sergey V. Avakyan . Proceedings of the SPIE, Volume 4853, pp. 306-317

The Dutch Open Telescope (DOT) is an innovative solar telescope, completely open, on an open steel tower, without a vacuum system. The aim is long-duration high resolution imaging and in order to achieve this the DOT is equipped with a diffraction limited imaging system in combination with a data acquisition system designed for use with the speckle masking reconstruction technique for removing atmospheric aberrations. Currently the DOT is being equipped with a multi-wavelength system forming a high-resolution tomographic imager of magnetic fine structure, topology and dynamics in the photosphere and low- and high chromosphere. Finally the system will contain 6 channels: G-band (430.5 nm), Ca II H (K) (396.8 nm), H-alpha (656.3 nm), Ba II (455.4 nm), and two continuum channels (432 and 651 nm). Two channels are in full operation now and observations show that the DOT produces real diffraction limited movies (with $0.2''$ resolution) over hours in G-band (430.5 nm) and continuum (432 nm).

**NLTE in a Hot Hydrogen Star: Auer & Mihalas Revisited**

Wiersma, J.; Rutten, R. J.; Lanz, T.

Stellar Atmosphere Modeling, ASP Conference Proceedings, Vol. 288. Abstracts from a conference held 8-12 April 2002 in Tuebingen, Germany. Editors: Ivan Hubeny, Dimitri Mihalas, and Klaus Werner. San Francisco: Astronomical Society of the Pacific, ISBN: 1-58381-131-1, 2003, p.130

We pay tribute to two landmark papers published by Auer & Mihalas in 1969. They modeled hot-star NLTE-RE hydrogen-only atmospheres, using two simplified hydrogen atoms: ApJ 156, 157: H I levels 1, 2 and c, Lyman alpha the only line ApJ 156, 681: H I levels 1, 2, 3 and c, Balmer alpha the only line and computed LTE and NLTE models with the single line turned on and off. The results were extensively analyzed in the two papers. Any student of stellar line formation should take these beautiful papers to heart. The final exercise in Rutten's lecture notes "Radiative Transfer in Stellar Atmospheres" asks the student to work through five pages of questions concerning diagrams from the first paper alone! That exercise led to the present work in which we recompute the Auer-Mihalas hot-hydrogen-star models with TLUSTY, adding results from a complete hydrogen atom for comparison.

Our motivation for this Auer-Mihalas re-visitation is twofold:

1. to add diagnostic diagrams to the ones published by Auer & Mihalas, in particular Bnu, Jnu, Snu graphs to illustrate the role of the radiation field, and radiative heating and cooling graphs to illustrate the radiative energy budget,

2. to see the effect of adding the rest of the hydrogen atom.

**Utrecht Radiative Transfer Courses**

Rutten, R. J.

Stellar Atmosphere Modeling, ASP Conference Proceedings, Vol. 288. Abstracts from a conference held 8-12 April 2002 in Tuebingen, Germany. Editors: Ivan Hubeny, Dimitri Mihalas, and Klaus Werner. San Francisco: Astronomical Society of the Pacific, ISBN: 1-58381-131-1, 2003, p.99

The Utrecht course "The Generation and Transport of Radiation" teaches basic radiative transfer to second-year students. It is a much-expanded version of the first chapter of Rybicki & Lightman's "Radiative Processes in Astrophysics". After this course, students understand why intensity is measured per steradian, have an Eddington-Barbier feel for optically thick line formation, and know that scattering upsets LTE. The text is a computer-aided translation by Ruth Peterson of my 1992 Dutch-language course. My aim is to rewrite this course in non-computer English and make it web-available at some time. In the meantime, copies of the Peterson translation

are made yearly at Uppsala – ask them, not me. Eventually it should become a textbook. The Utrecht course "Radiative Transfer in Stellar Atmospheres" is a 30-hour course for third-year students. It treats NLTE line formation in plane-parallel stellar atmospheres at a level intermediate between the books by Novotny and Boehm-Vitense, and Mihalas' "Stellar Atmospheres". After this course, students appreciate that epsilon is small, that radiation can heat or cool, and that computers have changed the field. This course is web-available since 1995 and is regularly improved – but remains incomplete. Eventually it should become a textbook.

The three Utrecht exercise sets "Stellar Spectra A: Basic Line Formation", "Stellar Spectra B: LTE Line Formation", and "Stellar Spectra C: NLTE Line Formation" are IDL-based computer exercises for first-year, second-year, and third-year students, respectively. They treat spectral classification, Saha-Boltzmann population statistics, the curve of growth, the FAL-C solar atmosphere model, the role of H-minus in the solar continuum, LTE formation of Fraunhofer lines, inversion tactics, the Feautrier method, classical lambda iteration, and ALI computation. The first two sets are web-available since 1998; the third will follow.

Acknowledgement. Both courses owe much to previous Utrecht courses taught by the late Kees Zwaan. The third exercise set was developed by Phil Judge, Mandy Hagenaar, and Thijs Krijger.

Reverse acknowledgement. If you are a user of this free material you might refer to this summary and so boost my citation standing. Corrections are also welcome.

**What can an urban observer do? Video work from downtown**

Bettonvil, F.

WGN, Journal of the International Meteor Organization, vol. 31, no. 2, p. 38-42

This paper demonstrates that, even from light polluted areas, useful meteor work can be done. In the center of a medium sized city an intensified video system was set up and the goal, instead of activity monitoring, was to do some orbit analysis. In April 2001, around the Lyrid maximum, multi-station observations were conducted from two stations, and together 50 meteor trails containing five double-station meteors were collected. As an example, three Lyrids were analyzed and their orbits calculated. The results illustrate that it is quite possible to do this kind of work under less favorable circumstances, but also showed some general problems with video multi-station work: neither radiant nor velocity could be determined accurately enough to compute all orbital elements precisely. Possible improvements to this are discussed.

**Large open telescope: size-upscaling from DOT to LOT**

Hammerschlag, Robert H.; Jaegers, Aswin P. L.; Bettonvil, Felix C. M.

Innovative Telescopes and Instrumentation for Solar Astrophysics. Edited by Stephen L. Keil, Sergey V. Avakyan. Proceedings of the SPIE, Volume 4853, pp. 294-305

The design characteristics of a large open telescope (LOT) are: (i) an open tower with only pure translations of the platform under wind load; (ii) an open telescope construction with extremely stiff geometry and drives; (iii) simple optics with easy aligning and testing, but nevertheless suitable for large auxiliary equipment like spectrographs.

**Motions of Isolated G-Band Bright Points in the Solar Photosphere**
Nisenson, P.; van Ballegooijen, A. A.; de Wijn, A. G.; Sütterlin, P.
The Astrophysical Journal, Volume 587, Issue 1, pp. 458-463

Magnetic elements on the quiet Sun are buffeted by convective flows that cause lateral motions on timescales of minutes. The magnetic elements can be observed as bright points (BPs) in the G band at 4305 $\AA$. We present observations of BPs based on a long sequence of G-band images recorded with the Dutch Open Telescope and postprocessed using speckle-masking techniques. From these images we measured the proper motions of isolated BPs and derived the autocorrelation function of their velocity relative to the solar granulation pattern. The accuracy of BP position measurements is estimated to be less than 23 km on the Sun. The rms velocity of BPs (corrected for measurement errors) is about 0.89 km $s^{-1}$, and the correlation time of BP motions is about 60 s. This rms velocity is about 3 times the velocity measured using cork tracking, almost certainly due to the fact that isolated BPs move more rapidly than clusters of BPs. We also searched for evidence of vorticity in the motions of G-band BPs.

**Intensity Oscillations in the upper transition region above active region plage**
de Pontieu, B.; Erdélyi, R.; de Wijn, A.; Loefdahl, M.
American Geophysical Union, Fall Meeting 2003, abstract SH42B-0540
The Astrophysical Journal, Volume 595, Issue 1, pp. L63-L66

Although there are now many observations showing the presence of oscillations in the corona, almost no observational studies have focused on the bright upper transition region (TR) emission (so-called moss) above active region plage. Here we report on a wavelet analysis of observations (made with TRACE, the Transition Region and Coronal Explorer) of strong ( $\sim$ 5-15%) intensity oscillations in the upper TR footpoints of hot coronal loops. They show a range of periods from 200 to 600 seconds, typically persisting for 4 to 7 cycles. These oscillations are not associated with sunspots, as they usually occur at the periphery of plage regions. A majority of the upper TR oscillations are directly associated with upper chromospheric oscillations observed in H alpha , i.e., periodic flows in spicular structures.

The presence of such strong oscillations at low heights (of order 3,000 km) provides an ideal opportunity to study the propagation of oscillations from photosphere and chromosphere into the TR and corona, and improve our understanding of the magnetic connectivity in the chromosphere and TR. In addition, we use new high resolution observations of the photosphere and chromosphere, taken with the Swedish Solar Telescope, to shed light on the source of chromospheric mass flows such as spicules.

# Chapter 7

# High-Energy Astrophysics

Staff members: Prof.dr F. Verbunt
dr. J. in 't Zand (postdoc)
drs. C. Bassa, drs. R. Cornelisse, drs. F. Hulleman, drs. A.G.J. van Leeuwen (PhD)
P. den Hartog (undergraduate student)

## 7.1 Research

Research topics: mainly neutron stars, also white dwarfs and black holes
Neutron stars accreting matter from a binary companion (X-ray binaries): we observe(d) these with
BeppoSAX, ROSAT, AXAF, XMM: X-ray
JKT, WHT, VLT: visual light
research goals: find out with what properties neutron stars and black holes are formed, in particular with what mass, radius, magnetic field, and velocity? Which processes determine the properties of binaries with a black hole or neutron star?
theoretical research: binary evolution from detailed study of individual systems, and global study by population synthesis

Because of the common occurrence of X-ray sources in globular clusters we also investigate these and old open clusters observations:
ROSAT, AXAF, XMM: X-ray
JKT, WHT: visual light
research goals: properties of X-ray sources in clusters, the importance of close encounters between single stars and binaries as well as binary evolution for the evolution of the cluster as a whole.
theoretical research: tidal forces in close binaries.

## 7.2 Academic Publications

**A superburst from 4U 1254-69**
in't Zand, J. J. M.; Kuulkers, E.; Verbunt, F.; Heise, J.; Cornelisse, R.
Astronomy and Astrophysics, v.411, p.L487-L491

We report the detection with the BeppoSAX Wide Field Cameras of a superburst from 4U 1254-69. The superburst is preceded by a normal type-I X-ray burst, has a decay time that is the longest of all eight superbursts detected so far and a peak luminosity that is the lowest. Like for the other seven superbursts, the origin is a well-known type-I X-ray burster with a persistent luminosity level close to one tenth of the Eddington limit. Based on WFC data of all persistently bright X-ray bursters, the average rate of superbursts is $0.51 \pm 0.25$ per year per persistently bright X-ray burster. Some systems may have higher superburst rates. For all superbursters, we present evidence for a pure helium layer which is burnt in an unstable as well as a stable manner.

**Optical identification of the companion to PSR J1911-5958A, the pulsar binary in the outskirts of NGC 6752**
Bassa, C. G.; Verbunt, F.; van Kerkwijk, M. H.; Homer, L.
Astronomy and Astrophysics, v.409, p.L31-L34

We report on the identification of the optical counterpart of the binary millisecond pulsar PSR J1911-5958A, located in the outskirts of the globular cluster NGC 6752. At the position of the pulsar we find an object with V=22.08, B-V=0.38, U-B=-0.49. The object is blue with respect to the cluster main sequence by 0.8 mag in B-V. We argue that the object is the white dwarf companion of the pulsar. Comparison with white dwarf cooling models shows that this magnitude and colors are consistent with a low-mass white dwarf at the distance of NGC 6752. If associated with NGC 6752, the white dwarf is relatively young, la 2 Gyr, which sets constraints on the formation of the binary and its ejection from the core of the globular cluster.

**Dynamical Formation of Close Binary Systems in Globular Clusters**
Pooley, David; Lewin, Walter H. G.; Anderson, Scott F.; Baumgardt, Holger; Filippenko, Alexei V.; Gaensler, Bryan M.; Homer, Lee; Hut, Piet; Kaspi, Victoria M.; Makino, Junichiro; Margon, Bruce; McMillan, Steve; Portegies Zwart, Simon; van der Klis, Michiel; Verbunt, Frank
The Astrophysical Journal, Volume 591, Issue 2, pp. L131-L134

We know from observations that globular clusters are very efficient catalysts in forming unusual short-period binary systems or their offspring, such as low-mass X-ray binaries (LMXBs; neutron stars accreting matter from low-mass stellar companions), cataclysmic variables (white dwarfs accreting matter from stellar companions), and millisecond pulsars (rotating neutron stars with spin periods of a few milliseconds). Although there has been little direct evidence, the overabundance of these objects in globular clusters has been attributed by numerous authors to the high densities in the cores, which leads to an increase in the formation rate of exotic binary systems through close stellar encounters. Many such close binary systems emit X-radiation at low luminosities ($L_X \lesssim 10^{34}$ ergs $s^{-1}$) and are being found in large numbers through observations with the Chandra X-Ray Observatory. Here we present conclusive observational evidence of a link between the number of close binaries observed in X-rays in a globular cluster and the stellar encounter rate of the cluster. We also make an estimate of the total number of LMXBs in globular clusters in our Galaxy.

**Bursts, eclipses, dips and a refined position for the luminous low-mass X-ray binary in the globular cluster Terzan 6**
in't Zand, J. J. M.; Hulleman, F.; Markwardt, C. B.; Méndez, M.; Kuulkers, E.; Cornelisse, R.; Heise, J.; Strohmayer, T. E.; Verbunt, F.
Astronomy and Astrophysics, v.406, p.233-243

GRS 1747-312 is a bright transient X-ray source in the globular cluster Terzan 6 with quasi-periodic outbursts approximately every 4.5 months. We carried out 2-60 keV target-of-opportunity observations during eight outbursts with the Proportional Counter Array on the RXTE satellite, for a total exposure time of 301 ks, and detect the first unambiguous thermonuclear X-ray bursts from this source. This identifies the compact accretor in this binary as a neutron star. The neutron star identification implies that twelve out of thirteen luminous (above $10^{36}$ erg $s^{-1}$) X-ray sources in Galactic globular clusters harbor neutron stars, with AC211's nature (in M15) remaining elusive. We observed 24 transitions of eclipses of the X-ray emitting region by the companion star and are able to improve the accuracy of the orbital period by a factor of 104. The period is P=0.514980303(7) d. We do not detect a period derivative with an upper limit of $|\dot{P}/P| = 3^{*}E^{-8}yr^{-1}$. Archival Chandra data were analyzed to further refine the X-ray position, and the cluster's center of gravity was re-determined from optical data resulting in a correction amounting to 2 core radii. We find that GRS 1747-312 is 0.2+/-0.2 core radii from the cluster center.

**Six years of BeppoSAX Wide Field Cameras observations of nine galactic type I X-ray bursters**
Cornelisse, R.; in't Zand, J. J. M.; Verbunt, F.; Kuulkers, E.; Heise, J.; den Hartog, P. R.; Cocchi, M.; Natalucci, L.; Bazzano, A.; Ubertini, P.
Astronomy and Astrophysics, v.405, p.1033-1042

We present an overview of BeppoSAX Wide Field Cameras observations of the nine most frequent type I X-ray bursters in the Galactic center region. Six years of observations (from 1996 to 2002) have amounted to 7 Ms of Galactic center observations and the detection of 1823 bursts. The 3 most frequent bursters are GX 354-0 (423 bursts), KS 1731-260 (339) and GS 1826-24 (260). These numbers reflect an unique dataset. We show that all sources have the same global burst behavior as a function of luminosity. At the lowest luminosities ($LX \lesssim 2^{*}E^{37}$ erg s$^{-1}$) bursts occur quasi-periodically and the burst rate increases linearly with accretion rate (clear in e.g. GS 1826-24 and KS 1731-260). At $L_{\rm pers} = 2^{*}E^{37}$ erg s$^{-1}$ the burst rate drops by a factor of five. This corresponds to the transition from, on average, a hydrogen-rich to a pure helium environment in which the flashes originate that are responsible for the bursts. At higher luminosities the bursts recur irregularly; no bursts are observed at the highest luminosities. Our central finding is that most of the trends in bursting behavior are driven by the onset of stable hydrogen burning in the neutron star atmosphere. Furthermore, we notice three new observational fact which are difficult to explain with current burst theory: the presence of short pure-helium bursts at the lowest accretion regimes, the bimodal distribution of peak burst rates, and an accretion rate that is ten times higher than predicted at which the onset of stable hydrogen burning occurs. Finally, we note that our investigation is the first to signal quasi-periodic burst recurrence in KS 1731-260, and a clear proportionality between the frequency of the quasi-periodicity and the persistent flux in GS 1826-24 and KS 1731-260.

**Photospheric radius expansion X-ray bursts as standard candles**
Kuulkers, E.; den Hartog, P. R.; in't Zand, J. J. M.; Verbunt, F. W. M.; Harris, W. E.; Cocchi, M. Astronomy and Astrophysics, v.399, p.663-680

We examined the maximum bolometric peak luminosities during type I X-ray bursts from the persistent or transient luminous X-ray sources in globular clusters. We show that for about two thirds of the sources the maximum peak luminosities during photospheric radius expansion X-ray bursts extend to a critical value of $3.79 \pm 0.15^{*}E^{38}$ erg s$^{-1}$, assuming the total X-ray burst emission is entirely due to black-body radiation and the recorded maximum luminosity is the actual peak luminosity. This empirical critical luminosity is consistent with the Eddington luminosity limit for hydrogen poor material. Since the critical luminosity is more or less always reached during photospheric radius expansion X-ray bursts (except for one source), such bursts may be regarded as empirical standard candles. However, because significant deviations do occur, our standard candle is only accurate to within 15%. We re-evaluated the distances to the twelve globular clusters in which the X-ray bursters reside.

**Sub-Subgiants in the Old Open Cluster M67?**
Mathieu, Robert D.; van den Berg, Maureen; Torres, Guillermo; Latham, David; Verbunt, Frank; Stassun, Keivan
The Astronomical Journal, Volume 125, Issue 1, pp. 246-259.

We report the discovery of two spectroscopic binaries in the field of the old open cluster M67-S1063 and S1113-whose positions in the color-magnitude diagram place them $\sim 1$ mag below the subgiant branch. A ROSAT study of M67 independently discovered these stars to be X-ray sources. Both have proper-motion membership probabilities greater than 97%; precise center-of-mass velocities are consistent with the cluster mean radial velocity. S1063 is also projected within one core radius of the cluster center. It is a single-lined binary with a period of 18.396 days and an orbital eccentricity of 0.206. S1113 is a double-lined system with a circular orbit having a period of 2.823094 days. The primary stars of both binaries are subgiants. The secondary of S1113 is likely a 0.9 Msolar main-sequence star, which implies a $1.3M_{\rm solar}$ primary star. We have been unable to explain securely the low apparent luminosities of the primary stars. The colors of S1063 suggest 0.15 mag higher reddening than found for either M67 or through the entire Galaxy in the direction of M67. S1063 could be explained as an extincted M67 subgiant, although the origin of such enhanced extinction is unknown. The photometric properties of S1113 are well modeled by a cluster binary with a $0.9M_{\rm solar}$ main-sequence secondary star. However, the low composite luminosity requires a small ($2.0R_{\rm solar}$) primary star that would be super-synchronously rotating, in contrast to the short synchronization timescales, the circular orbit, and the periodic photometric variability with the orbital period. Geometric arguments based on a tidally relaxed system suggest a larger ($4.0R_{\rm solar}$) primary star in a background binary, but such a large star violates the observed flux ratio. Thus, we have not been able to find a compelling solution for the S1113 system. We speculate that S1063 and S1113 may be the products of close stellar encounters involving binaries in the cluster environment and may define alternative stellar evolutionary tracks associated with mass transfer episodes, mergers, and/or dynamical stellar exchanges.

**Temperature and cooling age of the white dwarf companion of PSR J0218+4232**

Bassa, C. G.; van Kerkwijk, M. H.; Kulkarni, S. R.
Astronomy and Astrophysics, v.403, p.1067-1075

We report on Keck optical BVRI images and spectroscopy of the companion of the binary millisecond pulsar PSR J0218+4232. A faint bluish (V=24.2, B-V=0.25) counterpart is observed at the pulsar location. Spectra of this counterpart reveal Balmer lines which confirm that the companion is a helium-core white dwarf. We find that the white dwarf has a temperature of $T_{\rm eff} = 8060 \pm 150$ K. Unfortunately, the spectra are of insufficient quality to put a strong constraint on the surface gravity, although the best fit is for low $\log g$ and hence low mass ($\sim 0.2M_{\rm sun}$), as expected. We compare predicted white dwarf cooling ages with the characteristic age of the pulsar and find similar values for white dwarf masses of 0.19 to $0.3M_{\rm sun}$. These masses would imply a distance of 2.5 to 4 kpc to the system. The spectroscopic observations also enable us to estimate the mass ratio between the white dwarf and the pulsar. We find q =7.5 $\pm$ 2.4, which is consistent with the current knowledge of white dwarf companions to millisecond pulsars.

**Unusual Subpulse Modulation in PSR B0320+39:**
van Leeuwen, A.G.J.
A&A 402, 321-329

We report on an analysis of the drifting subpulses of PSR B0320+39 that indicates a sudden step of $\sim 180$ degrees in subpulse phase near the centre of the pulse profile. The phase step, in combination with the attenuation of the periodic subpulse modulation at pulse longitudes near the step, suggests that the patterns arise from the addition of two superposed components of nearly opposite drift phase and differing longitudinal dependence. We argue that since there cannot be physical overlap of spark patterns on the polar cap, the drift components must be associated with a kind of 'multiple imaging' of a single polar cap 'carousel' spark pattern. One possibility is that the two components correspond to refracted rays originating from opposite sides of the polar cap. A second option associates the components with emission from two altitudes in the magnetosphere.

**Probing drifting and nulling mechanisms through their interaction in PSR B0809+74**
van Leeuwen, A.G.J.
A&A 399, 223-229

Both nulling and subpulse drifting are poorly understood phenomena. We probe their mechanisms by investigating how they interact in PSR B0809+74. We find that the subpulse drift is not aliased but directly reflects the actual motion of the subbeams. The carousel-rotation time must then be over 200 seconds, which is much longer than theoretically predicted. The drift pattern after nulls differs from the normal one, and using the absence of aliasing we determine the underlying changes in the subbeam-carousel geometry. We show that after nulls, the subbeam carousel is smaller, suggesting that we look deeper in the pulsar magnetosphere than we do normally. The many striking similarities with emission at higher frequencies, thought to be emitted lower too, confirm this. The emission-height change as well as the striking increase in carousel-rotation time can be explained by a post-null decrease in the polar gap height. This offers a glimpse of the circumstances needed to make the pulsar turn off so dramatically.

## 7.3 Dissertations

15-01-2003; R. Cornelisse
Supervisors: Prof.dr F.W.M. Verbunt, prof.dr J. Heise
*A wide field view of the population of X-ray bursters in the galaxy*

14 -04-2003; F. Hulleman
Supervisor: prof.dr F.W.M. Verbunt
*Anomalous X-ray pulsars at optical and infrared wavelengths*

# Chapter 8

# Academic Reputation

Achterberg

- ASTRON Board
- Netherlands Committee on Astronomy (NCA)
- NOVA Board

Bettonvil

- Member Site Properties Sub committee (SUCOSIP) of the Oberservatorio del Roque de los Muchachos on La Palma and the Observatorio del Teide on Tenerife

Bleeker

- NLR-NIVR member Sub committee Space Technique, Scientific Committee NLR-NIVR
- member Netherlands Committee on Astronomy NCA
- co-chairman Science Steering Committee, Italian-Dutch X-ray Satellite (SAX)
- member IAU Commission 44 on Space and High Energy Astrophysics
- COSPAR Associate, Scientific Commission E on Research in Astrophysics from Space
- Member Programme Executive Committee, Italian-Dutch X-ray satellite (SAX)
- Member European Low Gravity Research Association (ELGRA)
- Member Koninklijke Nederlandse Akademie van Wetenschappen
- Member Academia Europea

- Member Hollandsche Maatschappij der Wetenschappen
- Co-chairman XMM-Science Working Team (ESA-mission scientist)
- Member Selection committee International Space University (ISU)
- Member Editorial Board Space Science Reviews
- Advisor Netherlands Industrial Space Organisation (NISO)
- Member European Astronomical Society (EAS)
- Board member Foundation for Experimental and Technical Physics
- Advisory member board Netherlands Research school for Astronomy (NOVA)
- Dutch delegate Science Programme Committee (SPC) of the European Space Agency (ESA)
- Member Board of Trustees, Basic Sciences, International Academy of Astronautics (IAA)
- Advisory member Interdepartmental Commission for Space (ICR)
- Member advisory board Foundation SPACE
- Member scientific advisory commission Anton Pannekoek of the University of Amsterdam
- Member advisory board of the NIVR
- Member board of Physics and Astronomy of the KNAW
- Member XEUS Science Advisory Group
- Member Scientific Organizing Committee "High Energy Astrophysics Symposium" for the 32nd COSPAR assembly
- Chair European Space Physical Sciences Panel ESSC/ESF
- Member ad hoc panel "New initiatives for large-scale collaborative space missions", ESSC/ESF

Goedbloed

- Board of NCF (National Computing Facilities Foundation)
- Program Committee Computational Science NWO

Hammerschlag

- Member Operations Sub-Committee (OSC) of the Observatorio del Roque de los Muchachos on La Palma

Lamers

- Netherlands Foundation for Radio Astronomy (NFRA/ASTRON), board member
- Leidsch-Kerkhoven Bosscha Fonds, member Board of Directors
- Leidse Sterrenwacht Foundation, member Board of Directors
- Kapteyn Foundation, board member
- Pastoor Schmeitz Foundation, board member
- Olga Koning Foundation, director
- Minnaert Committee for Popularization of Astronomy, member
- Mentor for PhD students of the Faculty of Physics and Astronomy

Langer

- Advisory committee of Astronomy of the Gebiedsbestuur Exacte Wetenschappen of NWO
- Program Committee of Hubble Space Telescope
- Program Committee of the European Southern Observatory (ESO)
- Lorentz Center Advisory Board
- Advisor Deutsche Forschungsgemeinschaft
- Advisor Australian Research Council

Pols

- Time allocation Committee of the Netherlands Foundation for Research in Astronomy (NFRA)

Rutten

- Professor II, Institute of Theoretical Astrophysics, Oslo University
- Member NOVA Instrument Steering Committee
- Member National Astronomy Education Committee
- Member editorial Board Solar Physics

Verbunt

- NOVA Board
- Netherlands Committee on Astronomy (NCA)
- Member of HST TAC on Globular Clusters
- Member of CGRO TAC

# Chapter 9

# Education

## 9.1 Student research in astronomy

Astrovaria, Bachelor, and Masters research projects in astronomy may be supervised by SIU and SRON staff members, postdocs, and graduate students. The overall responsibility always lies with an SIU or SRON staff member.
An Astrovaria measures 7.5 ects (5 weeks full-time),
Bachelor research projects are 15 ects (10 weeks = 1 ”periode’),
Masters research projects are 60 ects (one year).

The selection of a supervisor, the definition of a research project, and its scheduling are a matter of negotiation between student and potential supervisor. This is a free market mechanism in which the student should take the initiative. Find out who is doing what, identify research topics and supervisors that suit you, and then enter into negotiation with the appriopriate staff member.

The pertinent SIU weblink and SRON weblink may help you to select potential research areas and potential supervisors. Attending SIU student seminars and SIU-SRON lunch talks is also a good way to familiarize yourself with SIU and SRON research and researchers.

Your research should start with formal ”onderzoeksagenda” registration.

Presentations: a Bachelor research project must be reported at its completion in a SIU student seminar. A Masters research project must be outlined initially, after a few weeks of literature study, in a SIU student seminar and be presented at its completion in a SIU-SRON lunch talk. Masters-research poster presentation at the yearly Nederlandse Astronomenconferentie is highly recommended.

# Chapter 10

# Guests

dr. Tiit Nugis, Estonia, 2-24 April
drs. Paola Re Fiorentin, Italy, April-May-June
dr. Richard de Grijs, England,
dr. Annette Ferguson, Germany, 4-7 August
dr. C.J. Schrijver, California, 14-15 August

# Chapter 11

# Colloquia

| | | |
|---|---|---|
| January 16 | X-ray Timing and Spectral Properties of the ULXs | Dr. Tod Strohmayer NASA/GSFC |
| January 22 | Flow collisions in astrophysics: far from stationary and full of surprises | Dr. Rolf Walder Steward Observatory, University of Arizona |
| January 29 | The Atacama Large Millimeter Array: Science Drivers and Project Status | Prof. Ewine van Dishoeck Leiden Observatory |
| February 5 | Gamma-ray bursts: Black holes shining brightly? | Prof. Ralph Wijers Astronomical Institute 'Anton Pannekoek,' Amsterdam |
| February 12 | The Search for the Quark-Gluon-Plasma at the Relativistic Heavy Ion Collider | Prof. Dr. Thomas Peitzmann Utrecht University |
| February 26 | Some Like It Hot - News from Old Stars | Dr. Sabine Moehler Kiel University |
| March 5 | Two-dimensional models of protoplanetary disks: Walls and shadows around Herbig Ae/Be stars | Dr. Kees Dullemond MPA, Garching |
| March 12 | The Timescales of Galaxy Formation: Clues from Stellar Populations | Dr. Scott Trager Kapteyn Institute, Groningen |
| March 19 | The Copernican Revolution Reconsidered | Prof. Owen Gingerich CfA, Harvard University |
| March 26 | Chandra Observations of the Black widow pulsar B1957+20 | Dr. Ben Stappers ASTRON and Univ. of Amsterdam |
| March 28 | X-ray Astronomy - The Early Pioneering Years | Prof. Walter Lewin MIT |
| April 2 | The Age, Luminosity Function and Metallicity distribution of the Galactic Bulge | Dr. Manuela Zoccali ESO |
| April 9 | The Importance of AGB Stars to Galactic Chemical Evolution | Dr. John Lattanzio Monash University, Australia |
| April 16 | Ultraluminous X-ray Sources | Prof. Andrew King University of Leicester |

| | | |
|---|---|---|
| April 17 | Globular Clusters Formed in Gas-rich Galaxy Mergers: Implications For the Formation of Spheroidal Stellar Systems | Dr. Paul Goudfrooij STScI |
| April 23 | Stellar Abundances in Local Group Dwarf Galaxies: Clues to Formation and Chemical Evolution | Dr. Kim Venn Macalester College, Minnesota |
| April 25 | Probing Galaxy Formation and Evolution with the Local Universe Fossil Record | Dr. Annette Ferguson MPA, Munich |
| May 7 | The Rocket Science of Launching Stellar Disks | Dr. Stan Owocki UCL and University of Delaware |
| June 18 | Binary post-AGB stars | Dr. Hans van Winckel Astronomical Institute, Leuven |
| June 25 | New German solar telescopes in the first decade of the 21st century | Dr. Wolfgang Schmidt Kiepenheuer Institut fuer Sonnenphysik, Freiburg |
| August 7 | Stardust from Meteorites | Maria Lugaro Institute of Astronomy, Cambridge |
| September 10 | The colliding winds in the WR+LBV binary system HD 5980 | Gloria Koenigsberger Instituto de Astronomia UNAM, Mexico |
| September 24 | Westerland 1 - window on massive stellar evolution | Simon Clark University College, London |
| September 30 | Present Status and Future Programme of Japanese Space Science | K. Yamashita Nagoya University, Japan |
| October 1 | Non-microlensing applications of microlensing surveys: Galactic extinction | Piotr Popowski MPA, Munich |
| October 8 | Circumstellar dust in C-rich environments | Sacha Hony ESTEC |
| October 15 | Astrophysical jets and magnetized accretion disks | Fabien Casse FOM, Rijnhuizen |
| October 22 | X-ray emission and origin of runaway stars | Evert Meurs Dunsink Observatory, Ireland |
| October 28 | WMAP: the Cosmic Microwave Background | David Spergel Princeton University Observatory |
| November 5 | X-ray and Gamma-ray observations of Cas A: Exposing Core Collapse to the Core | Jacco Vink SRON |
| November 19 | Geomagnetic reversals as a stochastic exit problem | Peter Hoyng SRON |
| December 9 | Exciting Stellar Morbidity | Bruce Balick Univ. of Washington, Seattle |
| December 10 | Formation, evaporation and growth of Primordial Black Holes | Jorge Horvath Univ. of Sao Paulo, Brazil |

Colloquia are held every Wednesday at 15:30h at either the Sterrekundig

Instituut Utrecht, Minnaertzaal, Buijs Ballotlaboratorium, Princetonplein 5, 3584 CC Utrecht or the SRON: Stichting RuimteOnderzoek Nederland, Conferentiezaal Sorbonnelaan 2, 3584 CA Utrecht
E-mail: Mariano Mendez, M.Mendez@sron.nl (SRON)
Onno Pols, O.R.Pols@astro.uu.nl (SIU)
WWW: http://www.astro.uu.nl/colloq

# Chapter 12

# Staff

Name, Telephone, Room

Prof.dr. A. Achterberg, 5211, 753
drs. C.G. Bassa, 5227, 702a
drs. N. Bastian, 5235, 762
dr. J. Bergmans, 5213, 751
ir. F.C.M. Bettonvil, 5218, 707
Prof.dr.ir. J.A.M. Bleeker, 5732, SRON
drs. C. Ferrrigno, 5200, SRON
mw. drs. P.-K. Fung, 5213, 751
drs. M. Gieles, 5204, 760
Prof.dr. J.P. Goedbloed, 5212, 752
dr.ir. R.H. Hammerschlag, 5220, 708a
dr. A. Helmi, 760, 5204
dr. S.J. Hogeveen, 5230, 701a
P.W. Hoogendoorn, 5215, CBG
dr. D. Khechinashvili, 5212, 752
mw. dr. M. Kraus, 5204, 760
Prof.dr. H.J.G.L.M. Lamers, 5222, 709
Prof.dr. N. Langer, 5210, 708b
drs. J. Leenaarts, 5206, 758
drs. A.J. van Marle, 2235, 762a
dr. J. Petri, 5223, 701b
drs. J. de Plaa, 5712, SRON
drs. A.J.T. Poelarends, 5227, 702a
dr. O.R. Pols, 5209, 755
Prof.dr. R.J. Rutten, 5226, 704
drs. M.V. van der Sluys, 5234, 759
F. Snik, 5218, 767
dr. P. Suetterlin, 5225, 702b
mw. drs. I.M. Stegeman, 5235, 762
dr. K. Tziotziou ,5206, 758
Prof.dr. F.W.M. Verbunt, 5207, 757

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drs. A.G. de Wijn, 5225, 702b
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| | |
|---|---|
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| Peter Nolet | advisor O. Pols |
| Dagmar de Rooij | advisor A. Achterberg |
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| Teffie Schneider | advisor A. Achterberg |
| Tim Tsarfati | advisor A. Achterberg |
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# Chapter 13

# Full list of publications

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