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Regina von Berlepsch

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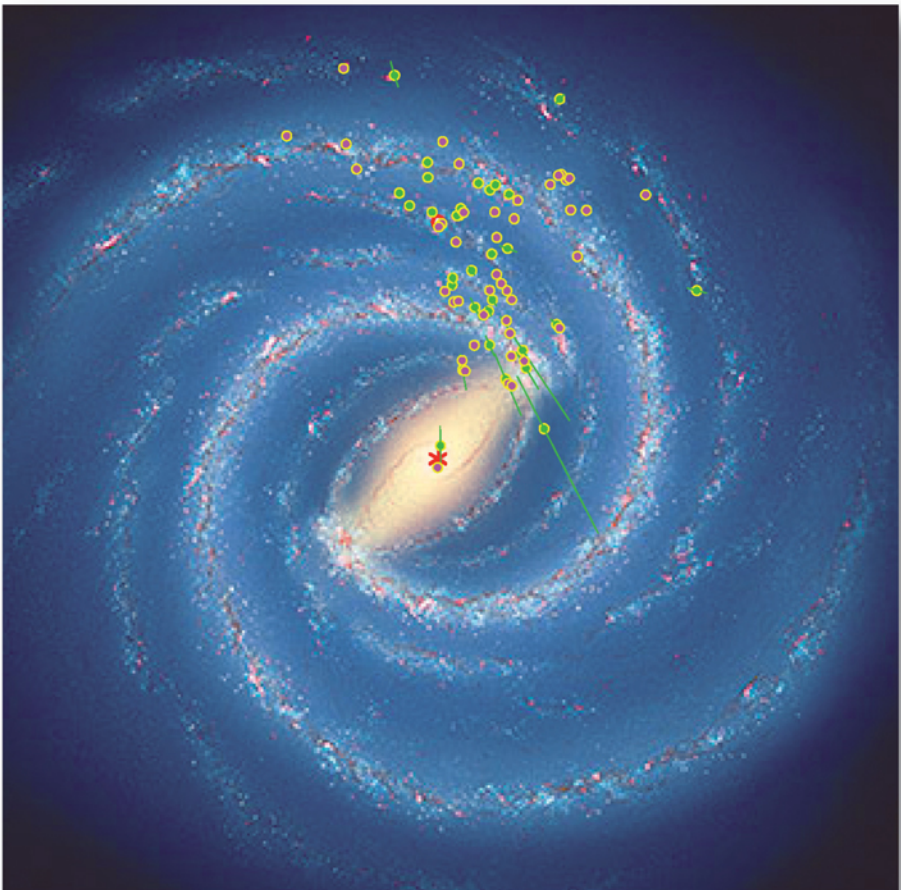
23 Zooming in: The Cosmos at High Resolution



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Vol. 23

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Zooming in: The Cosmos at High Resolution

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Edited on behalf of the Astronomische Gesellschaft by

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Cover
Artist conception of the Milky Way (R. Hurt: NASA/JPL-Caltech/SSC) showing all sources currently measured (green), including unpublished sources, and all sources observed in the first year of BeSSeL (red), based on their kinematic distances (A. Brunthaler et al.; this book).

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Preface

The annual series *Reviews in Modern Astronomy* of the ASTRONOMISCHE GESELLSCHAFT was established in 1988 in order to bring the scientific events of the meetings of the Society to the attention of the worldwide astronomical community. *Reviews in Modern Astronomy* is devoted to the Karl Schwarzschild Lectures, the Ludwig Biermann Award Lectures, the invited reviews, and to the Highlight Contributions from leading scientists reporting on recent progress and scientific achievements at their respective research institutes.

The Karl Schwarzschild Lectures constitute a special series of invited reviews delivered by outstanding scientists who have been awarded the Karl Schwarzschild Medal of the Astronomische Gesellschaft, whereas excellent young astronomers are honoured by the Ludwig Biermann Prize.

Volume 23 continues the series with fourteen invited reviews and Highlight Contributions which were presented during the International Scientific Conference of the Society on “Zooming in: The Cosmos at High Resolution” held in Bonn, Germany, September 13 to 17, 2010.

The Karl Schwarzschild medal 2010 was awarded to Professor Michel Mayor, Genf. His lecture with the title “Exoplanets: The road to Earth twins” opened the meeting.

The talk presented by the Ludwig Biermann Prize winner 2010, Dr. Maryam Modjaz, Berkeley, dealt with the topic “Stellar Forensics with the Supernova-GRB connection”.

In 2010 the Doctoral Thesis Award was established by the Astronomische Gesellschaft to honor the author of the most outstandig Doctoral Thesis of the past year. The first awardee was Hans Moritz Günther. His lecture with the title “Accretion, jets and winds: High-energy emission from young stellar objects” was one of the highlights of the conference.

Other contributions to the meeting published in this volume discuss, among other subjects, the gas history of the universe, the facility for antiproton and ion research, the Bar and Spiral Structure Legacy (BeSSeL) survey and star formation at high resolution.

A report on the Herschel Key Program “Water in star-forming regions with Herschel” completes this volume.

The editor would like to thank the lecturers for their stimulating presentations. Thanks also to the local organizing committee from the Argelander Institute for Astronomy and the Max Planck Institute for Radio Astronomy.

Potsdam, Mai 2011 *Regina v. Berlepsch*

The Astronomische Gesellschaft awards the **Karl Schwarzschild Medal**. Awarding of the medal is accompanied by the Karl Schwarzschild lecture held at the scientific annual meeting and the publication. Recipients of the Karl Schwarzschild Medal are

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1963 Charles Fehrenbach:
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Dreißig Jahre Kometenforschung.
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Thick accretion disks around black holes.
Mitteilungen der AG 57, 27

1982 Jean Delhaye:
Die Bewegungen der Sterne
und ihre Bedeutung in der galaktischen Astronomie.
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on the Role of Numerical Modeling in Astrophysics.
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Reviews in Modern Astronomy 22, 1

2010 Michel Mayor:
Exoplanets: The road to Earth twins
Reviews in Modern Astronomy 23, 1

The **Ludwig Biermann Award** was established in 1988 by the ASTRONOMISCHE GESELLSCHAFT to be awarded in recognition of an outstanding young astronomer. The award consists of financing a scientific stay at an institution of the recipient's choice. Recipients of the Ludwig Biermann Award are

1989	Dr. Norbert Langer (Göttingen),
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1993	Dr. Andreas Burkert (Garching),
1994	Dr. Christoph W. Keller (Tucson, Arizona, USA),
1995	Dr. Karl Mannheim (Göttingen),
1996	Dr. Eva K. Grebel (Würzburg) and Dr. Matthias L. Bartelmann (Garching),
1997	Dr. Ralf Napiwotzki (Bamberg),
1998	Dr. Ralph Neuhäuser (Garching),
1999	Dr. Markus Kissler-Patig (Garching),
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2005	Dr. Philipp Richter (Bonn),
2007	Dr. Henrik Beuther (Heidelberg) and Dr. Ansgar Reiners (Göttingen),
2008	Dr. Andreas Koch (Los Angeles),
2009	Dr. Anna Frebel (Cambridge, USA) and Dr. Sonja Schuh (Göttingen),
2010	Dr. Maryam Modjaz (Berkely),

The **The Doctoral Thesis Award** was established in 2010 by the ASTRONOMISCHE GESELLSCHAFT to honor the author of the most outstandig Doctoral Thesis of the past year. Recipient of the first Doctoral Thesis Award is

2010	Dr. Hans M. Günther (Cambridge/MA),

Contents

Karl Schwarzschild Lecture

The road to Earth twins[1]

Michel Mayor, Christophe Lovis, Francesco Pepe,
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Abstract

A rich population of low-mass planets orbiting solar-type stars on tight orbits has been detected by Doppler spectroscopy. These planets have masses in the domain of super-Earths and Neptune-type objects, and periods less than 100 days. In numerous cases these planets are part of very compact multiplanetary systems. Up to seven planets have been discovered orbiting one single star. These low-mass planets have been detected by the HARPS spectrograph around 30 % of solar-type stars. This very high occurrence rate has been recently confirmed by the results of the Kepler planetary transit space mission. The large number of planets of this kind allows us to attempt a first characterization of their statistical properties, which in turn represent constraints to understand the formation process of these systems. The achieved progress in the sensitivity and stability of spectrographs have already led to the discovery of planets with masses as small as 1.5 $M_\oplus$.

1 The discovery of a rich population of low mass planets on tight orbits

Today, more than 500 extrasolar planets have been discovered. Most of the detected exoplanets have been found by using precise measurements of stellar radial velocities. The planetary mass estimate from Doppler measurements is directly proportional to the amplitude of the stellar reflex motion. Our progress to detect very-low-mass planets are directly related to the progress done to improve the sensitivity and stability of spectrographs. In 1989, the detection of HD 114762 b, a companion of 11 Jupiter masses to a metal deficient F star was obtained with spectrographs allowing Doppler measurements with a precision of some 300 m s^{-1} (Latham et al. 1989). Fifteen years ago, the precision achieved by any team searching for exoplanets was of

[1]This article has already appeared in Astron. Nachr./AN 332, no. 5 (2011).

Reviews in Modern Astronomy 23: Zoomimg in: The Cosmos at High Resolution. First Edition.
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the order of $15\,\mathrm{m\,s^{-1}}$. Today, the instrumental precision achieved with the HARPS spectrograph at La Silla Observatory is better than $0.5\,\mathrm{m\,s^{-1}}$ (Mayor et al. 2003). At this level of precision we are mostly limited by the intrinsic variability of stellar velocities induced by diverse phenomena (acoustic modes, granulation, magnetic activity). However, by adopting an improved observing strategy, we have already some indications that planetary signals as small as a tiny fraction of a meter per second are detectable.

This progress in instrumentation and observing strategy have made possible the discovery of a rich population of super-Earths and Neptune-mass planets in tight orbits around solar-type stars (Mayor & Udry 2008).

The name “super-Earth" is used to qualify planets more massive than the Earth but with masses smaller than 10 Earth masses, a category of planets absent in the solar system. We mention here a few landmark discoveries of these low-mass planets orbiting solar-type stars. Limiting ourself to planets in the super-Earth range we can mention: μ Ara c with a mass of $10.5\,\mathrm{M_\oplus}$ and a period of 9.7 days (Santos et al. 2004b, revised in Pepe et al. 2007), HD 69830 b with a mass of $10.2\,\mathrm{M_\oplus}$ and a period of 8.7 days (Lovis et al. 2006), HD 40307 b, c, d, a system with three super-Earths with masses comprised between 4 and $9\,\mathrm{M_\oplus}$ and periods from 4 to 20 days (Mayor et al. 2009b). We also have to mention the exceptional system around HD 10180, with 7 planets of which one with a mass as small as $1.4\,\mathrm{M_\oplus}$ on a tight orbit with a period of 1.17 day (Lovis et al. 2011). In addition to these early detections of super-Earths orbiting solar-type stars, we also have to mention the discoveries of super-Earths hosted by M dwarfs: GJ 876 d, a planet with a mass of $5.9\,\mathrm{M_\oplus}$ and a period of 1.94 day (Rivera et al. 2005, Correia et al. 2010), GJ 581 c, d, e with masses of 5, 7, and $1.9\,\mathrm{M_\oplus}$ (Udry et al. 2007; Mayor et al. 2009a). It is impressive to see that all these super-Earths are part of rich multi-planetary systems with 3 to 7 planets per system. The remarkable progress of instrumentation in the last 15 years is obvious in Fig. 1. The masses of planetary companions are plotted as a function of the epoch of their discovery. The mass of HD 10180 b (Lovis et al. 2011) is a factor 100 smaller than the mass of 51 Peg b (Mayor & Queloz 1995).

2 The HARPS program to search for very low mass planets

HARPS is a vacuum-operated high-resolution spectrograph ($R = 115\,000$), fiber-fed, optimized to provide stellar radial-velocity measurements with extreme precision (Mayor et al. 2003). As a reward for its construction, the HARPS consortium has received guaranteed observing time (GTO) to carry out an extrasolar planet search in the southern hemisphere (500 observing nights over 5 years). More than 60 % of the total HARPS GTO observing time has been devoted to two sub-programs having the aim of detecting very low-mass planets. The first of these sub-programs comprises some 400 stars which are non-active, slow rotators, not in spectroscopic binary systems, and were selected from the large volume-limited sample measured for several years with the CORALIE spectrograph on the 1.2 m-Euler telescope at la Silla Observatory. The second sub-program consists of a volume-limited sample of about

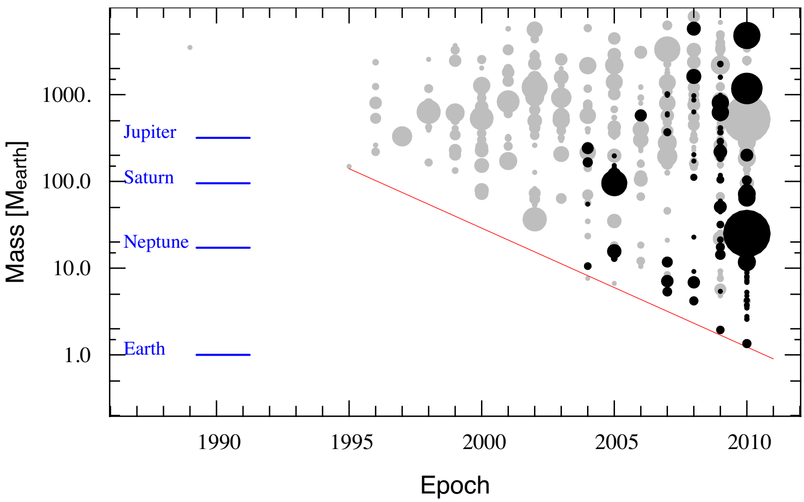

Figure 1: (online colour at: www.an-journal.org) Minimum mass of planets detected by Doppler spectroscopy as a function of epoch of discovery. This figure illustrates the impressive progress made in detection sensitivity over the past 15 years. Black symbols indicate HARPS discoveries. Dot size is related to orbital semi-major axis.

120 M dwarfs at the bottom of the main sequence, also selected to be slow rotators and not members of spectroscopic binary systems.

What are the limits presently achieved in terms of radial velocity precision? Several sources of noise can be identified:

- As a result of the efficiency of the cross-correlation technique, a photon noise level of only a fraction of a meter per second is achieved in a few minutes for most of our targets. Sometimes the exposure time is shorter than the typical periods of stellar acoustic modes. In a few minutes, the full amplitude of the stellar velocity variations resulting from acoustic modes could be as large as several meters per second. Long integrations compared to acoustic mode periods are sufficient to have acoustic noise residuals smaller than 0.2 $\mathrm{m\,s^{-1}}$ (rms). For most stars, integrations of 15 minutes are sufficient.

- Dumusque et al. (2011a) have shown that stellar granulation in solar-type stars can induce radial velocity variability comparable to or larger than 1 $\mathrm{m\,s^{-1}}$ on longer timescales compared to acoustic modes. Several measurements spanning several hours are requested to damp the granulation noise.

- Any anisotropies in stellar atmospheres related to magnetic activity will induce radial velocity variations at the stellar rotation period. The amplitude of the radial-velocity jitter is related with stellar chromospheric activity. If we want to search for very low mass planets we need to carefully select “non-active" stars . The reemission in the core of the calcium H and K lines is a good indicator of the chromospheric activity and has been used for the selection of the stellar sample.

- The analysis of the radial velocity variations of several solar-type stars has recently revealed well-defined variations of several $\mathrm{m\,s^{-1}}$ on rather long periods (more than five years). These velocity variations are strongly correlated with the mean shape of absorption lines and chromospheric indicators like Ca II H and K core emission. These variations are related to the stellar analogs of the solar magnetic cycle. This effect has been observed in stars with rather modest chromospheric activity levels (e.g. $\log R'_{\mathrm{HK}}$ around –4.90, see Lovis et al. 2011b). Any long-term drift in stellar radial velocities cannot be a priori attributed to long period planets if a careful check of the long-term behavior of the line bisector and other activity indicators has not been performed.
- Finally, we still have instrumental noise. Lovis & Pepe (2007) have considerably improved the precision of the wavelength of thorium lines as well as the number of lines to be used for the calibration of the spectrograph. Pressure changes in the plasma with the aging of the ThAr calibration lamp induce a very small shift in the wavelengths. As this effect is smaller for thorium lines than argon, we can use this differential effect to correct the aging effect. Long term drifts have thus been reduced below $0.3\,\mathrm{m\,s^{-1}}$ over timescales of several years. The scrambling effect in optical fibers is excellent ... but not perfect and some sub-meter per second error could result from imperfect guiding.

The global budget of all these errors is difficult to determine. The best estimation of the lower limit of the quadratic sum of the different components of the noise is provided by the residuals observed around fitted radial velocity curves. Several stars with a very large number of velocity measurements spanning several years have residuals with a dispersion as low as $0.6\,\mathrm{m\,s^{-1}}$ (when binning the data over a few days). For stars with larger chromospheric activity, we can obviously have larger residuals.

This is the precision presently achieved for the HARPS program, for which we have derived preliminary results for the population of low mass planets, as discussed in the next section. If we are searching for low-mass planets on rather long periods, it could be useful to bin the measurements done on N consecutive nights. This procedure could help to damp the noise induced by chromospheric activity, with a time scale comparable to the stellar rotation period. First experiments done on stars with a large number of measurements have shown that the residuals decrease to 0.3–$0.5\,\mathrm{m\,s^{-1}}$ after binning over ten consecutive nights.

3 Emerging characteristics of low-mass planets and their host star

We are still far from having a detailed and unbiased view of the population of planets with masses in the range of super-Earths and Neptunes. Nevertheless, we can already notice a few emerging properties. The study of planet hosts themselves also provide additional information to constrain planet formation. In particular the metallicity of the parent stars seems to be of prime importance for models of planetary formation.

3.1 The mass distribution

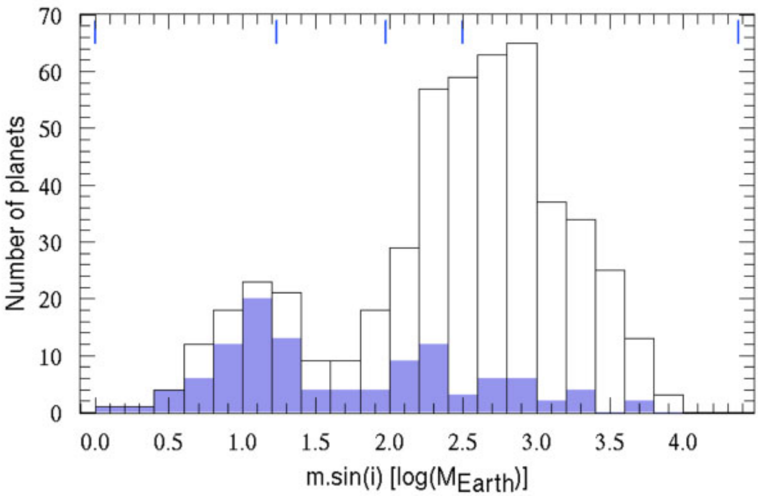

Figure 2: (online colour at: www.an-journal.org) Mass distribution of all detected planets. The contribution of the HARPS program (solid histogram) for the detection of very low mass planets is evident.

The mass distribution of all detected planets is illustrated in Fig. 2. In this plot the contribution of the HARPS program for the detection of very low mass planets is evident. Due to the better detection sensitivity of Doppler spectroscopy for massive and/or short period planets, we still have a strong bias against the detection of low-mass planets, especially if they are on long-period orbits.

The bimodal aspect of the mass distribution is a clear indication that the decrease of the distribution for masses less than about one mass of Jupiter is not the result of a detection bias, but is real. The extrapolation by a power-law distribution, as for example $f(m) \sim m^{-1}$, to estimate the number of planets with a mass smaller than the mass of Jupiter is certainly not justified. The observed bimodal shape of the mass distribution from gaseous giant planets to the super-Earth regime provides an interesting constraint for planetary formation scenarios. The planetary formation simulations carried out by Mordasini et al. (2009a,b) also predict a bimodal distribution for that range of planetary mass. In addition these simulations also predict a sharp rise in the mass distribution at a few Earth masses and below. This domain of mass is still at the limit of present instrumental sensitivity. Nevertheless, once again the expected shape of this theoretical mass distribution from 10 down to $1\,M_\oplus$ is clearly not an exponential and any estimate of the frequency of Earth-twins based on an exponential extrapolation is completely unjustified.

3.2 The frequency of low-mass multiplanet systems

With the HARPS data presently available from the high-precision sample, we have 48 stars with well-characterized planetary systems. More than 50 % of these systems are multiplanetary. Four of them have 4 planets and the amazing system HD 10180 is the host of 7 planets (Lovis et al. 2011a), one of them having a mass as small as 1.5 $M_{\oplus}$.

3.3 The correlation with the metallicity of host stars

The correlation between the occurrence of gaseous giant planets and the metallicity of host stars is striking. Based on large planetary surveys this correlation is well established by independent teams (Santos, Israelian & Mayor 2001, 2004a; Fischer & Valenti 2005). We have a completely different result if we examine the metallicity of host stars for systems having all planets less massive than 40 $M_{\oplus}$. We do not have any correlation between the presence of these low-mass planets and the host star metallicity (see Fig. 3), a result already mentioned by Udry et al. (2006) and Sousa et al. (2008), based at that time on a very limited number of stars. With the present study, this lack of correlation with the host star metallicity is robust. The mean metallicity of the 28 planetary systems with planets less massive than 40 $M_{\oplus}$ is [Fe/H] = –0.12, a metallicity not so different from the mean metallicity of stars in the solar neighborhood.

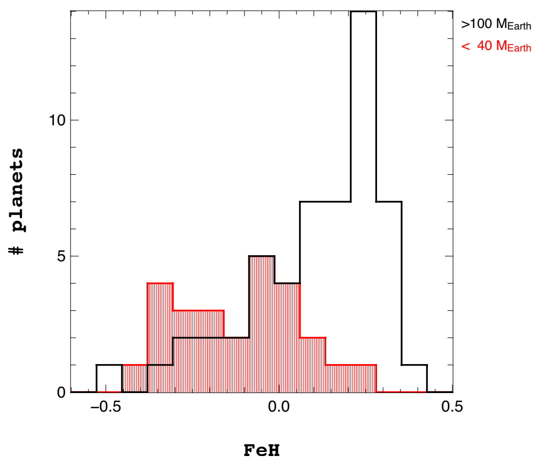

Figure 3: (online colour at: www.an-journal.org) Number of planets as a function of host star metallicity. Planets with masses smaller than 40 $M_{\oplus}$ are hosted by stars of all metallicities, contrary to giant planets whose frequency is strongly dependent on host star metallicity.

3.4 The occurrence of low-mass planets orbiting solar-type stars

The occurrence of low-mass planets on tight orbits has been estimated by Lovis et al. (2009). For planets with masses between ∼5 and 50 $M_\oplus$ and periods shorter than 100 days, we have detected low-mass planets orbiting about 30 % of the stars in the HARPS sample. A more complete estimate is currently in progress, based on the present, more complete survey.

3.5 Searching for Earth-type planets in the habitable zone

The programme devoted to the study of the population of super-Earths and Neptune-type planets is still continuing at la Silla for four additional years after the end of the GTO time. In addition, a new exploratory program has been initiated with the goal of pushing the HARPS precision a little further and try to detect super-Earths in the habitable zone of very nearby G and K dwarfs. An adequate strategy to damp the acoustic and granulation noise sources has been implemented. The sample is limited to only 10 bright non-active stars. Already, low-mass planets have been detected around three stars members of that small sample, see Pepe et al. (2011). The radial velocity signal for one of these planets is as small as $K = 0.56$ m s^{-1}. Furthermore, simulations done by Dumusque et al. (2011b) have demonstrated the possibility with the HARPS spectrograph, the present observing strategy and precision, to detect a 2.5 $M_\oplus$ planet orbiting a non-active K dwarf in its habitable zone (see Fig. 4).

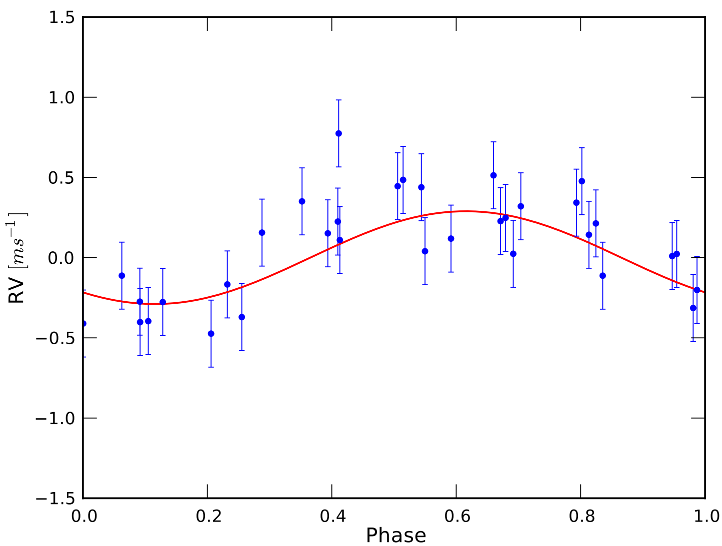

Figure 4: (online colour at: www.an-journal.org) Simulation for the detection of a super-Earth of 2.5 $M_\oplus$ in the habitable zone of an inactive K dwarf (from Dumusque et al. 2011b).

Some technical improvements are still feasible to increase the sensitivity and stability of cross-correlation spectrographs like HARPS. A better scrambling of the input beam could be achieved by new optical fibers with octagonal cross sections. These new fibers will strongly diminish the already very small effect of input conditions (guiding errors, variable seeing and focus) on the spectrograph illumination, a mandatory condition to achieve $0.1\,\mathrm{m\,s^{-1}}$ precision. To secure the stability of radial velocity measurements over a span of several years at the level of $0.1\,\mathrm{m\,s^{-1}}$ or better, we must have a calibration device better than the existing ThAr lamps. Developments of laser frequency combs adapted to the resolution and wavelength coverage of HARPS will provide the requested stability (Wilken et al. 2010).

A photon noise on the Doppler signal at the level of $0.1\,\mathrm{m\,s^{-1}}$ requires a rather large telescope size to achieve the needed signal-to-noise ratio in a reasonable exposure time. The ESPRESSO project, presently in development, to be implemented on the 8.2-m VLT telescope at Paranal is designed to achieve the $0.1\,\mathrm{m\,s^{-1}}$ Doppler precision and stability on the long term (Pepe et al. 2010). The ESPRESSO project can also be seen as a precursor for an even more ambitious stable spectrograph, the CODEX project presently at the study phase level for the 42-m E-ELT telescope, to be implemented by ESO at Cerro Armazones (Chile) in the next decade (Pasquini et al. 2010).

We have to keep in mind that for stars with the lowest chromospheric activity, we still do not know the true level of radial velocity jitter. Analysis of the radial velocity scatter of HARPS measurements for non-active stars suggest a minimum jitter of $0.5\,\mathrm{m\,s^{-1}}$ or less. This stellar variability, depending on the changing number and phase of magnetic spots (or other features) will be difficult to model. Preliminary studies show that non-active K dwarfs will be the most suitable targets to search for Earth twins. A large number of Doppler measurements has the potential to overcome the effects of the stellar intrinsic variability and permit detections of planetary signals of $0.2\,\mathrm{m\,s^{-1}}$ or less.

The discovery of radial velocity variations associated with solar cycle analogues with full amplitude as large as $10\ \mathrm{m\,s^{-1}}$ seems a priori to be casting doubts on our ability to detect Earth analogues in the habitable zone. However, using parameters of the cross-correlation function it has been possible to correct the magnetic cycle effects to less than $1\,\mathrm{m\,s^{-1}}$. In addition, for some domain of stellar masses (K dwarfs), we observe that the amplitude of the radial velocity effect is vanishing despite quite noticeable magnetic cycles. Finally, we notice that the periods of magnetic cycles are much longer (about a factor 10) than the expected periods of habitable planets orbiting K dwarfs. We are thus still convinced that Doppler spectroscopy has the potential to detect rocky planets in the habitable zone of K dwarfs.

The medium- or long-term scientific goal to search for chemical signatures of life in the atmospheric spectra of Earth twins via space experiments as the ESA-DARWIN concept will first require identification of targets. It seems that at the moment Doppler spectroscopy is the only method with the potential to detect Earth-type planets in the habitable zone of stars as close as possible to the Sun. The last condition is mandatory, if we want to have a star-planet angular separation large enough for the need of planetary atmosphere spectroscopy, as well as bright enough targets to maximize the signal-to-noise ratio.

From Doppler surveys we know that super-Earths on tight orbits are frequent. We have first hints from microlensing searches that super-Earths could also be frequent at large semi-major axis (Gould et al. 2010). But we do not have any estimate of the frequency of Earth-twins in the habitable zone of solar-type stars and no ideas on their orbital eccentricity distribution. The orbital eccentricity of Earth-twins is also relevant in the frame of life-search experiments. The ESA-PLATO space project is, in that context, the most interesting experiment, complementary to Doppler surveys to explore the domain of Earth-type planets orbiting relatively close stars.

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Ludwig Biermann Award Lecture

Stellar forensics with the supernova-GRB connection[1]

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Abstract

Long-duration gamma-ray bursts (GRBs) and type Ib/c supernovae (SNe Ib/c) are amongst nature's most magnificent explosions. While GRBs launch relativistic jets, SNe Ib/c are core-collapse explosions whose progenitors have been stripped of their hydrogen and helium envelopes. Yet for over a decade, one of the key outstanding questions is what conditions lead to each kind of explosion in massive stars. Determining the fates of massive stars is not only a vibrant topic in itself, but also impacts using GRBs as star formation indicators over distances up to 13 billion light-years and for mapping the chemical enrichment history of the universe. This article reviews a number of comprehensive observational studies that probe the progenitor environments, their metallicities and the explosion geometries of SN with and without GRBs, as well as the emerging field of SN environmental studies. Furthermore, it discusses SN 2008D/XRT 080109 which was discovered serendipitously with the Swift satellite via its X-ray emission from shock breakout and which generated great interest amongst both observers and theorists while illustrating a novel technique for stellar forensics. The article concludes with an outlook on how the most promising venues of research – with the many existing and upcoming large-scale surveys such as PTF and LSST – will shed new light on the diverse deaths of massive stars.

1 Introduction: the importance of stellar forensics

Stripped supernovae (SNe) and long-duration gamma-ray bursts (GRBs) are nature's most powerful explosions from massive stars. They energize and enrich the ISM, and, like beacons, they are visible over large cosmological distances. However, the exact mass and metallicity range of their progenitors is not known, nor the detailed physics of the explosion (see reviews by Woosley & Bloom 2006, and by Smartt 2009). Stripped-envelope SNe (i.e, SN IIb, Ib, Ic, and Ic-bl) are core-collapse events

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whose massive progenitors have been stripped of progressively larger amounts of their outermost H and He envelopes (Fig. 1, Clocchiatti et al. 1996; Filippenko 1997). In particular, broad-lined SNe Ic (SNe Ic-bl) are SNe Ic whose line widths approach $30\,000\ \mathrm{km\,s^{-1}}$ around before and around maximum light and whose optical spectra show no trace of H and He.

The exciting connection between long GRBs and SNe Ic-bl and the existence of SNe Ic-bl without observed GRBs, as well as that of GRBs that surprisingly lack SN signatures raises the question of what distinguishes a GRB progenitor from that of an ordinary SN Ic-bl with and without a GRB.

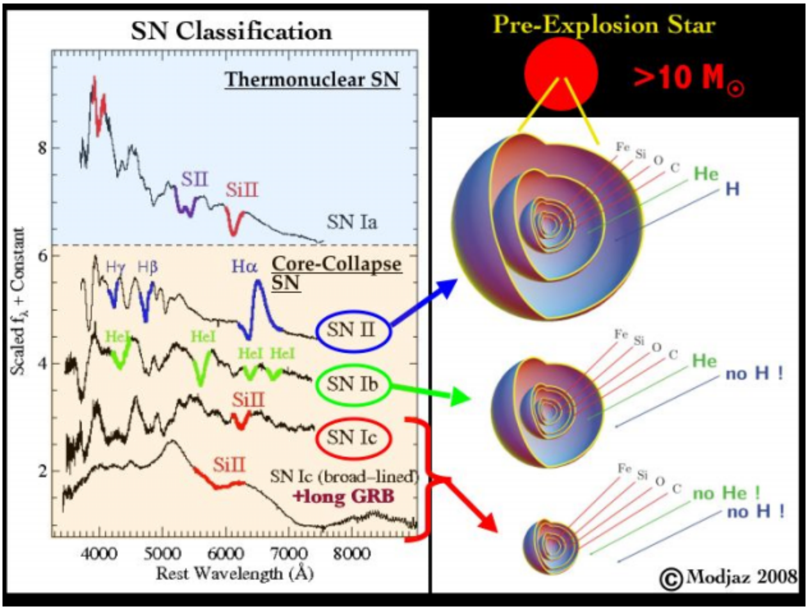

Figure 1: (online colour at: www.an-journal.org) Possible mapping between core-collapse SNe types (*left*) and their corresponding progenitor stars (*right*). *Left*: representative observed spectra of different types of SNe. Broad-lined SN Ic are the only type of SNe seen in conjunction with GRBs. Not shown are some of the H-rich members of the SN: SN IIn, and very luminous SN. *Right*: schematic drawing of massive ($\geq$8–10 $M_\odot$) stars before explosion, with different amounts of intact outer layers, showing the "onion-structure" of different layers of elements that result from successive stages of nuclear fusion during the massive stars' lifetimes. The envelope sizes are not drawn to scale; in particular, the outermost hydrogen envelope at the top can be up to 100 times larger than shown. Furthermore, many real massive stars rotate rapidly and are therefore oblate, as well as showing less chemical stratification as drawn here due to convection and overshoot mixing (e.g., see review by Woosley et al. 2002). The bottom star constitute the most stripped (or "naked") star which give rise to SN Ic and sometimes, SN Ic-bl and GRBs, One of the outstanding questions in the field is the exact mechanism with which the outer H and He layers got removed. This figure can be downloaded at http://www.astro.columbia.edu/~mmodjaz/research.html.

Understanding the progenitors of SN Ib/c and of GRB is important on a number of levels:

***Stellar and high-energy astrophysics*:** These stellar explosions leave behind extreme remnants, such as black holes, neutron stars, magnetars, which in themselves are a rich set of phenomena studied over the full wavelength spectrum from gamma-rays to radio. Ideally we would like to construct a map that connects the mass and make-up of a massive star to the kind of death it undergoes and to the kind of remnant it leaves behind. Furthermore, these stellar explosions are sources of gravitational waves and of neutrino emission, and specifically GRBs are leading candidate sites for high-energy cosmic ray acceleration (e.g., Waxman 2004). Thus, it is of broad astrophysical importance to understand the specific progenitor and production conditions for different kinds of cosmic explosions.

***Chemical enrichment history of the universe*:** The universe's first- and second-generation stars were massive. Since GRBs and SN probably contribute differently to the enrichment of heavy elements (e.g., Nomoto et al. 2006; Pruet et al. 2006), determining the fate of massive stars is fundamental to tracing the chemical history of the universe.

***Cosmology*:** GRBs are beacons and can illuminate the early universe. Indeed, until recently, the object with the highest spectroscopic redshift was a GRB, GRB 090423 at $z \sim 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009), which means that this explosion occurred merely 630 million years after the Big Bang. Thus, a clear understanding of the stellar progenitors of SN and GRBs is an essential foundation for using them as indicators of star formation over cosmological distances.

Various progenitor channels have been proposed for stripped SNe and GRBs: either single massive Wolf-Rayet (WR) stars with main-sequence (MS) masses of $\gtrsim$30 $M_\odot$ that have experienced mass loss during the MS and WR stages (e.g., Woosley et al. 1993), or binaries from lower-mass He stars that have been stripped of their outer envelopes through interaction (Fryer et al. 2007; Podsiadlowski et al. 2004, and references therein), possibly given rise to run-away stars as GRB progenitors (e.g., Cantiello et al. 2007; Eldridge et al. 2011). For long GRBs, the main models for a central engine that is powering the GRB include the collapsar model (MacFadyen & Woosley 1999; Woosley 1993) and the magnetar model (e.g., Usov 1992, for a good summary see Metzger et al. 2011), while rapid rotation of the pre-explosion stellar core appears to be a necessary ingredient for both scenarios.

Attempts to directly identify SN Ib/c progenitors in pre-explosion images obtained with the Hubble Space Telescope or ground-based telescopes have not yet been successful (e.g., Gal-Yam et al. 2005; Maund et al. 2005; Smartt 2009), and cannot conclusively distinguish between the two suggested progenitor scenarios. However, the progenitor non-detections of 10 SN Ib/c strongly indicate that the single massive WR progenitor channel (as we observe in the Local Group) cannot be the only progenitor channel for SN Ibc (Smartt 2009). Similar pre-explosion imaging technique is not possible for GRB progenitors given the large distances at which they are observed.

Thus, in order to fully exploit the potential and power of SNe and GRBs, we have to first figure out their stellar progenitors and the explosions conditions that lead to the various forms of stellar death in a massive star, in form of a "stellar forensics" investigation. In the following review, we will be looking at a number of physical properties in order to find those that set apart SN-GRB, which I will discuss in detail in Sect. 2, from SNe without GRBs: geometry of the explosion (Sect. 4), progenitor mass (Sect. 5) and metallicity (Sect. 6), while the role of binaries are discussed through-out, but not that of magnetic fields. In addition, I will discuss the exciting and emerging field of SN metallicity studies as a promising new tool to probe the progenitors of different kinds of SNe and transients and the story of SN 2008D/XRT 080109 (Sect. 7), which generated great interest amongst both observers and theorists while illustrating a novel technique for stellar forensics

Necessarily, this review will not be complete given the page limit, and is driven by the interest and work of the author, so omissions and simplifications will necessarily arise. Furthermore, given the excellent reviews by Woosley & Bloom (2006), and most recently, Hjorth & Bloom (2011), I will concentrate on developments in the field since 2006 and in complimentary areas.

2 Solid cases of SN-GRB

While the explanation for GRBs after their initial discovery included a vast array of different theories, intensive follow-up observations of GRBs over the last two decades have established that long-duration soft-spectra GRBs (Kouveliotou et al. 1993), or at least a significant fraction of them, are directly connected with supernovae and result from the cataclysmic death of massive, stripped stars (see review by Woosley & Bloom 2006). The most direct proof of the SN-GRB association comes from spectra taken of the GRB afterglows, where the spectral fingerprint of SN, specifically that of a broad-lined SN Ic, emerges over time in the spectrum of the GRB afterglow. Near maximum light, GRB-SNe appear to show broad absorption lines of O I, Ca II, and Fe II (see Fig. 1), while there is no photospheric spectrum of a confirmed GRB-SN that indicated the presence of H or showed optical lines of He I (see also below).

Below we briefly list the SN-GRB cases, in order of descending quality of data (see also Table 1 in Woosley & Bloom 2006 and detailed discussions in Hjorth & Bloom 2011). The five most solid cases of the SN-GRB connection, with high signal-to-noise and multiple spectra, are usually at low z: SN1998bw/GRB980425 at $z = 0.0085$ (Galama et al. 1998), SN2003dh/GRB030329 at $z = 0.1685$ (Hjorth et al. 2003; Matheson et al. 2003; Stanek et al. 2003), SN2003lw/GRB031203 at $z = 0.10058$ (Malesani et al. 2004), SN2006aj/GRB060218 at $z = 0.0335$ (Campana et al. 2006; Cobb et al. 2006; Kocevski et al. 2007; Mirabal et al. 2006; Modjaz et al. 2006; Pian et al. 2006; Sollerman et al. 2006), and most recently, SN2010bh/GRB100316D at $z = 0.0593$ (Chornock et al. 2011; Starling et al. 2011), where the SN spectra lines were visible as early as 2 days after the GRB, (Chornock