The UVES M Dwarf Planet Search Programme

Martin Kürster[1]
Mathias Zechmeister[1]
Michael Endl[2]
Eva Meyer[1]

[1] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[2] McDonald Observatory, University of Texas at Austin, USA

We present results from our search programme for extrasolar planets around M dwarfs carried out with UVES between 2000 and 2007 and enjoying ESO Large Programme status from April 2004 to March 2006. In our sample of 41 stars we have found one "brown dwarf desert" companion candidate, but no planetary mass companions. We have determined upper limits to the mass of possible companions, which, in the habitable zones of our better observed stars, reach the regime of a few Earth masses. Significant periodic variability observed in Barnard's star is attributed to stellar activity.

There are now first indications that M dwarf stars provide a less efficient environment for the formation of Jupiter-type planets than G–K main sequence stars, whereas Neptune-mass planets and planets with a few Earth masses ("Super-Earths") could be numerous around M dwarfs. It has also become clear that the striking paucity of brown dwarf companions orbiting G–K stars at separations of a few astronomical units (known as the "brown dwarf desert") extends into the M dwarf regime.

High precision differential radial velocity (RV) measurements of stellar reflex motions, induced by an orbiting companion, have so far been the most successful method of discovering extrasolar planets and characterising their orbital properties. Originally, RV planet search programmes mostly concentrated on main sequence stars of spectral types F7 through K with masses in the range 0.7–1.2 $M_\odot$. M dwarfs have only been included in search programmes in the last few years, because of their faintness requiring large telescopes and/or a substantial amount of observing time to perform RV measurements with a precision of the order of a few ms^{-1}. Among the more than 300 known extrasolar planets currently known, only thirteen planets accompanying eight different M dwarfs have orbits determined by RV measurements.

Table 1 lists all planets around M dwarfs so far discovered with the RV method. Masses are the minimum masses that correspond to the RV effect observable when viewing in the plane of the orbit. Since the RV method does not allow the determination of all parameters of the orientation of the orbit, only minimum masses are obtained. As can be shown, a viewpoint from within the plane of the orbit is the most probable case, so that these minimum masses are also the most probable masses. For two of the M dwarf planets, GJ 436b and GJ 876b, the true masses could be obtained. GJ 436b is observed to transit in front of its host star, thereby slightly dimming the star light, and confirming that we are really viewing from close to the orbital plane. For GJ 876b the astrometric displacement on the sky could be measured, which allows for the complete determination of the orientation of the orbit on the sky.

In this article we report on our RV monitoring programme of 41 M dwarfs carried out with the UVES spectrograph at UT2 on Paranal between 2000 and 2007 and enjoying ESO Large Programme status from April 2004 to March 2006 (Kürster et al., 2006). This programme was designed to search for terrestrial planets in the habitable zone of M dwarfs.

The first brown dwarf desert companion object around an "early-type" M dwarf (spectral types M0–M5) was found in this programme, but the small sample did not reveal any planetary companions. This is consistent with the small number (only 13 planets orbiting eight different M dwarfs) found to date by other RV surveys that are observing several hundred stars. In our sample we can exclude the presence of Jupiter-mass planets for a wide range of orbital periods. We did however find significant variability in Barnard's star that we attribute to stellar activity, thus indicating that this star may have non-solar surface convection patterns.

Why M dwarfs?

For an understanding of the formation and abundance of extrasolar planets, it is of utmost importance to determine the presence and orbital characteristics of planets around stars of as many different types as possible, and especially around the most abundant type of star, the M dwarfs. It is currently estimated that M dwarfs make up 70–75% of the stars in the Solar Neighbourhood and probably a similar figure holds for the fraction of M dwarfs in the Galaxy as a whole. M dwarfs have smaller masses than Solar-type stars. Dwarf stars of spectral types M0, M3 and M6 have, respectively, 0.5, 0.29 and 0.2 solar masses. The smaller the stellar mass the greater is its reflex motion induced by a planet. Given a sensitivity to find RV signals of a certain amplitude lower mass

Star	Components				Reference
	b	c	d	e	
GJ 876	**2.53 M_{Jup}**	0.79 M_{Jup}	7.53 $M_\oplus$		Delfosse et al. (1998), Marcy et al. (1998), Rivera et al. (2005)
GJ 581	15.7 $M_\oplus$	5.4 $M_\oplus$	7.1 $M_\oplus$	1.94 $M_\oplus$	Mayor et al. (2009), Bonfils et al. (2005), Udry et al. (2007)
GJ 436	**21 $M_\oplus$**				Butler et al. (2004)
GJ 317	0.71 M_{Jup}				Johnson et al. (2007)
GJ 674	11.1 $M_\oplus$				Bonfils et al. (2007)
GJ 849	0.82 M_{Jup}				Butler et al. (2006)
GJ 176	8.4 $M_\oplus$				Forveille et al. (2009)
GJ 832	0.64 M_{Jup}				Bailey et al. (2009)

Table 1. Masses of the RV-discovered planets around M dwarfs. Values in bold face are true masses (see text). All other values are minimum masses.

planets can be found around M dwarfs, and terrestrial planets of just a few Earth masses are within the reach of state-of-the-art spectrographs.

Another interesting characteristic of M dwarfs is that the potentially life-bearing region around it, called the "habitable zone", is much closer to the star than it is for Solar-type stars. Depending on the spectral subtype, the habitable zone corresponds to orbital periods from a few days to several weeks. This is a consequence of the low luminosity of M dwarfs. In the visual a dwarf star of spectral type M0, M3 or M6 is, respectively, 4.2, 6.9 or 11.8 magnitudes fainter than the Sun; their total luminosities reach just 6%, 3% or 0.5%, respectively, of the Solar value.

The habitable zone

The habitable zone is defined as that region around a star where liquid water can exist on a rocky planet with a suitable CO_2/ H_2O /N_2 atmosphere (Kasting et al., 1993). Here the key term is "suitable", which means that quite a number of atmospheric parameters need to have the right values. Overall, the term habitable zone is not a very well defined concept and it may well be that it will have to be expanded should life be found in more exotic environments.

M dwarfs and Jupiter-mass planets

Due to the low masses of M dwarfs, Jovian planets in orbits up to a few astronomical units (AUs) would be relatively easy to find with current precision RV surveys. To date only five such companions to M dwarfs have been found orbiting four different stars (see Table 1). First analyses indicate that the frequency of Jovian planets around M dwarfs is relatively low. Endl et al. (2006) have shown that it is below 1.27% for orbital separations up to one AU. This value is considerably higher around G–K main sequence stars, of which 2.5% are known to harbour Jovian planets within AU.

The UVES sample

Target selection for our UVES search programme was based on the following criteria. Since high resolution spectrographs strongly disperse the light and are therefore hungry for photons, all stars had to be brighter than V = 12 mag to achieve the necessary high RV measurement precision. With the exception of one misclassified M giant that had an erroneous distance entry in the catalogue of nearby stars, all stars are closer than 37 parsec.

The sample stars were also selected for small X-ray luminosity as an indicator of low levels of activity. To meet this criterion a star must either not have been detected in the ROSAT X-ray satellite all-sky survey or have an X-ray luminosity below 10^{27} $ergs^{-1}$ (Hünsch et al., 1999). Two exceptions to this rule are the known flare star Proxima Cen, which was included, since it is the star nearest to us, and the star GJ 229, which was known to have a wide brown dwarf companion at a separation of at least 44 AU (Nakajima et al., 1995). We initially selected 21 stars, but added another 20 when the survey became an ESO Large Programme in April 2004.

Achievable RV precision and allocated time

To achieve high RV measurement precision, the UVES spectrograph was used,

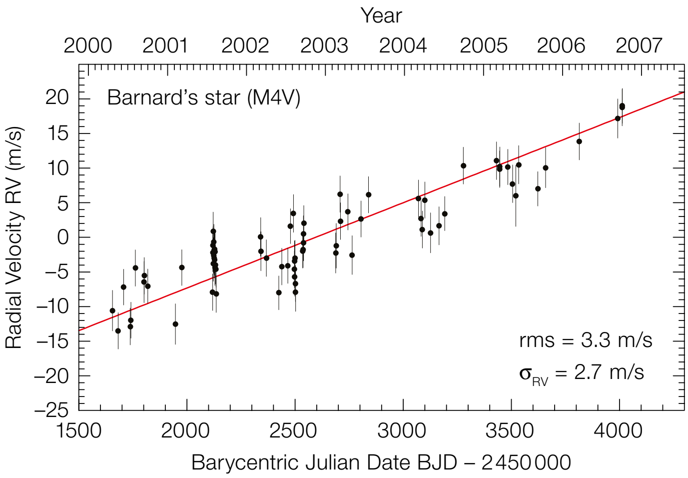


Figure 1. Time series of UVES differential RV measurements of Barnard's star. The solid line represents the predicted RV secular acceleration. The scatter of the data around this line (rms) and the RV measurement error (σ_{RV}) are listed in the plot.

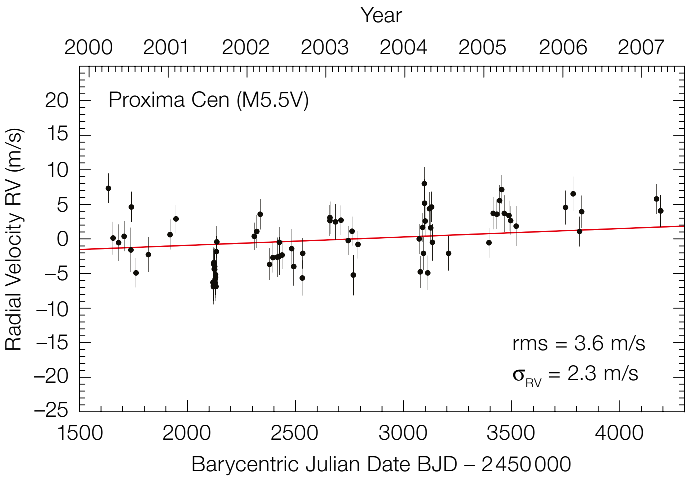


Figure 2. Same as Figure 1, but for Proxima Cen.

together with its iodine gas absorption cell, a self-calibrating device that corrects for instabilities of the instrument over time. The RV precision achievable in long exposures (i.e., with high signal-to-noise ratios) is 2 ms^{-1}, which corresponds to determining the position of the stellar spectrum on the CCD detectors to within 1/700 of a pixel, or 22 nm.

In order to make the best use of the time available time for our sample of stars, we decided to sacrifice some of the achievable RV precision and work at typical values of 2.5–4 ms^{-1}. The observing time allocated to our survey was 160 h for the four-semester Large Programme phase plus 280 h for nine single-semester normal programmes.

RV time series

The 41 stars in our sample were observed with different frequencies. The number of visits per star ranged from just two visits, for two of our stars (that were immediately identified as double-lined spectroscopic binaries and not followed up any further), up to 75 and 76 visits, respectively, for our best observed targets — Barnard's star and Proxima Centauri. On average we have 20 measurements per star and no more than one visit for any given star was made in a single night.

The RV time series for our best-observed stars are shown in Figure 1 (Barnard's star) and Figure 2 (Proxima Cen; see also Endl & Kürster, 2008). The data are shown together with a solid line corresponding to the predicted change in the RV of these nearby stars resulting from their movement on the sky, called the "RV secular acceleration". The RV can be defined as the change in distance of a star from us. When a star passes by us its RV is first negative, reaches zero at the point of closest approach and becomes positive afterwards. RV secular acceleration is thus an ever-increasing effect (see Kürster et al., 2003).

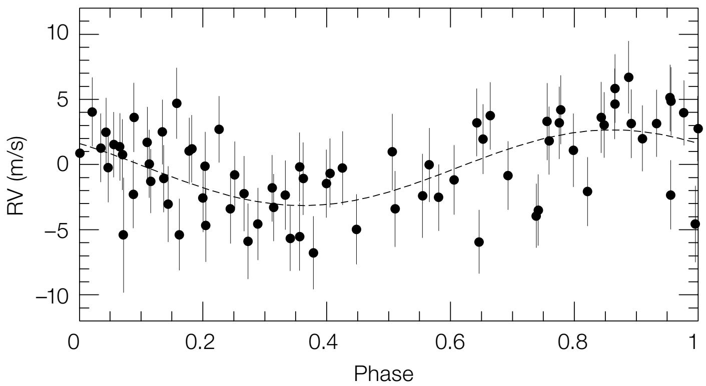


Figure 3. Differential RV data for Barnard's star phase-folded with a period of 44.9 d. The dashed line corresponds to the best-fitting sinusoidal variation.

RVs *v.* activity in Barnard's star

If this purely geometric effect is subtracted from the data, the data can then be subjected to period analysis in an attempt to find periodic signals that would be indicative of an orbiting companion. In the case of Barnard's star we find a significant signal with a period of 44.9 d and an RV amplitude of ± 2.9 ms^{-1} (Zechmeister et al., 2009; Kürster et al. 2003). Figure 3 shows the RV data phase-folded with this period. If this signal could be attributed to an orbiting companion, this object would be a Super-Earth with a minimum mass of 4.7 $M_{\oplus}$. It would orbit somewhat outside of the habitable zone of Barnard's star.

However, there are reasons to believe that the signal is produced by the star itself, i.e. by its surface activity and its influence on the convective motions that carry the heat transport from the interior to the outer regions of a low-mass star. When examining the line strength of the Hα line one finds the same 44.9 d periodicity. The Hα line originates in the stellar photosphere as an absorption line, but it has superimposed emission components generated in localised, so called "plage", regions in the chromosphere, a higher and hotter layer of the stellar atmosphere.

Examining in detail how the behaviour of the Hα line strength is correlated with our RV measurements we find evidence that the convection must be locally disturbed by the magnetic fields of active regions. While this is a well-known effect in Solar-type stars, where it causes a net blueshift of the stellar absorption lines, it appears that in Barnard's star a net redshift is produced, pointing at fundamental differences in the underlying behaviour of the surface convection of Solar-type stars and this M4 dwarf (see Kürster et al., 2003, for details).

Mass upper limits

Faced with the lack of a signal from an orbiting planet one can determine which types of planets can be excluded around a given star, because their signals would have been found. This kind of analysis requires detailed simulations in which signals of hypothetical planets are added to the observed data, and the modified data are subjected to the same tests that are employed to discover signals.

Figures 4 and 5 show the results of such simulations for Barnard's star and Proxima Cen, respectively (from Zechmeister et al., 2009). Upper limits to the mass of planets that would have been found are shown. They are plotted as a function of orbital distance of the planet from the star and of orbital period. In both figures vertical dashed lines delimit the habitable zone. In both cases planets with more than five Earth masses can be excluded from the habitable zone. Note again that these values correspond to the most probable viewing direction from within the orbital plane, so that a lower mass planet could still be hidden in our data, if the viewing angle were

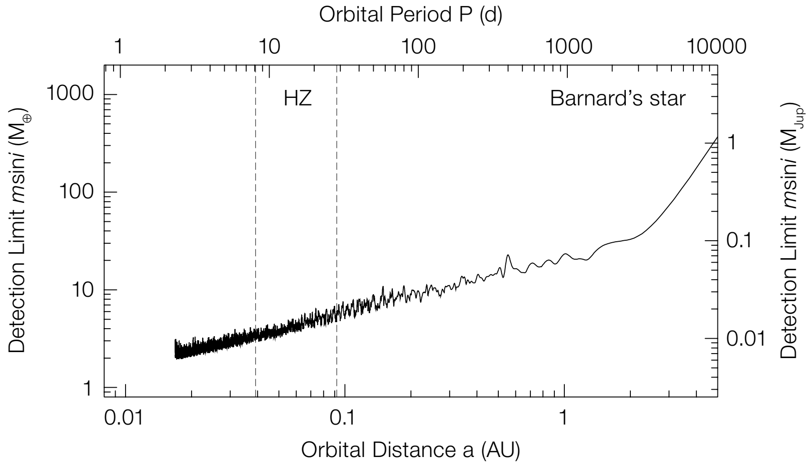


Figure 4. Upper limits to the projected mass *m*sin*i* of hypothetical planets around Barnard's star as a function of separation (lower *x*-axis) and orbital period (upper *x*-axis). Planets above the solid line would have been detected. Vertical dashed lines delimit the habitable zone (HZ).

grossly different. At 1 AU we exclude Neptune-mass (17 $M_\oplus$) planets, whereas Jupiter-mass (318 $M_\oplus$) planets should have been found at 5 AU.

For the majority of our stars for which we could not secure as many measurements as for Barnard's star and Proxima Cen, the same type of simulations lets us exclude planets with masses in the range between the masses of Neptune (17 $M_\oplus$) and Saturn (95 $M_\oplus$) from the habitable zone around the star.

Note that the necessary sensitivity to discover a given planetary signal depends very much on the phase of the signal with respect to the temporal measurement window. Data taken near the maxima and minima of the signal carry much more information than data taken at intermediate phases. In order to exclude a planet with a given mass, we must consider all possible phases, also those for which we are least sensitive. Therefore, our upper limits are relatively conservative. A lower-mass planet could still be discovered, if its RV signal has a favourable phase. If it corresponded to a planet, the 44.9-d signal in Barnard's star (Figure 3) would be an example.

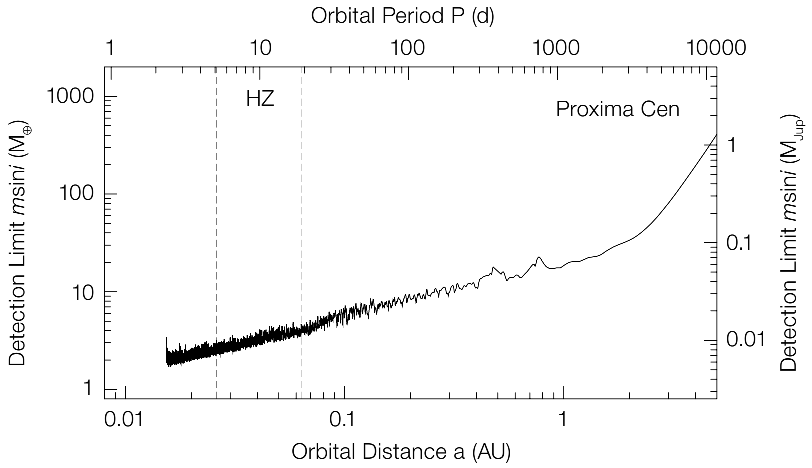


Figure 5. Same as Figure 4, but for Proxima Cen.

An oasis in the brown dwarf desert

So far no brown dwarfs in orbits up to a few AU around their host star ("brown dwarf desert" objects) have been found around M dwarfs of spectral types M0–M5. Our survey has now found the first such object, a companion to the M2.5 dwarf star GJ 1046 (Kürster et al., 2008). Figure 6 shows the RV time series along with the best-fitting Keplerian orbit with a period of 169 d and an eccentricity of 0.28. The star-companion separation is 0.42 AU.

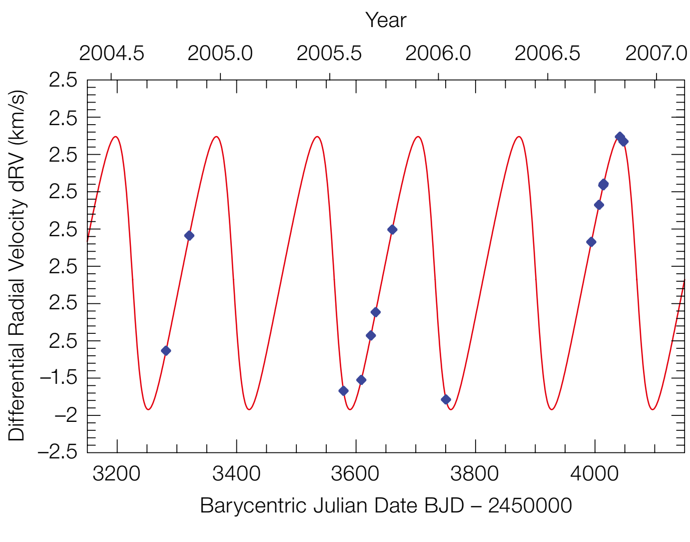


Figure 6. Time series of UVES differential RV measurements of GJ 1046 along with the best-fitting Keplerian orbit corresponding to a brown dwarf desert candidate.

From the RVs we determine a minimum mass of 26.9 Jupiter masses. Considering all possible orbital orientations we find a chance probability of 6.2% that the companion mass exceeds the mass threshold of 80 Jupiter masses between brown dwarfs and stars. When combining our RV data with the astrometric measurements made by the Hipparcos satellite (using the new reduction by van Leeuwen, 2007), we can place an upper limit to the companion mass of 112 Jupiter masses and narrow down the chance probability that the companion is a star to just 2.9%. Most likely, it is a genuine brown dwarf.

Astrometric follow-up

To determine the true mass of the companion to GJ 1046, and thereby its nature, we have begun an astrometric follow-up study with the NACO adaptive optics system and infrared camera at UT4 (Meyer & Kürster, 2008). We aim to measure the orbital reflex motion of GJ 1046 relative to a background star separated by just 30" on the sky. This chance encounter makes precise astrometric measurements possible, from which the orientation of the orbit, and hence the true mass of the companion, can be derived.

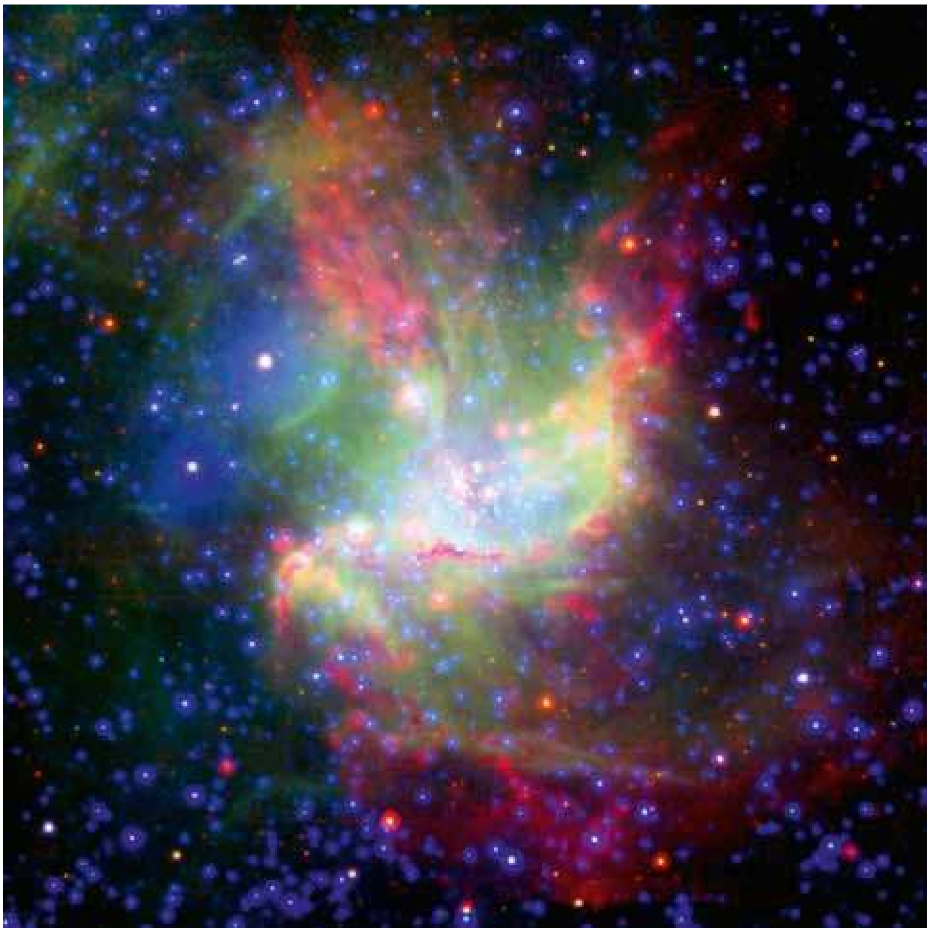
From our RV measurements we can predict that the astrometric signal is at least 3.7 milliarcseconds (peak-to-peak) corresponding to 14% of an image pixel in the employed NACO S27 camera, but, depending on the orientation of the orbit, the true signal may be considerably larger.

Acknowledgements

We thank the ESO Observing Programmes Committee and the Director's Discretionary Time Committee for generous allocation of observing time. We are also grateful to all of ESO staff who helped with the preparation of the service mode observations, carried them out, or processed, verified and distributed the data. A number of people have contributed in many ways to make this survey happen. Our thanks go to Stéphane Brillant, William D. Cochran, Sebastian Els, Artie P. Hatzes, Thomas Henning, Andreas Kaufer, Sabine Reffert, Florian Rodler, Frédéric Rouesnel and Steve S. Saar.

References

Endl M. et al. 2006, ApJ, 649, 436
Endl M. & Kürster M. 2008, A&A, 488, 1149
Hünsch M. et al. 1999, A&AS, 135, 319
Kasting, J. F. et al. 1993, Icarus, 101, 108
Kürster M. et al. 2003, A&A, 403, 1077
Kürster M., Endl M. & Rodler F. 2006, The Messenger, 123, 21
Kürster M., Endl M. & Reffert S. 2008, A&A, 483, 869
Meyer E., & Kürster M. 2008, in *Proceedings of the 15th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, AIP Conf. Proc. 1094, 549
Nakajima T. et al. 1995, Nature, 378, 463
van Leeuwen F. 2007, A&A, 474, 653
Zechmeister M., Kürster M. & Endl M. 2009, A&A, submitted



The star forming region NGC 346 in the Small Magellanic Cloud is shown in this colour composite image. The picture combines images from the infrared (NASA Spitzer Space Telescope, in red), the visible (ESO NTT, in green) and the X-ray (ESA XMM, in blue) to reveal the multi-component structure of dust, stars and hot gas. See ESO PR 55/07 for more details.