From the Dynamics of Cepheids to the Milky Way Rotation and the Calibration of the Distance Scale

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High precision spectroscopic measurements of ten southern Galactic Cepheid stars with the High Accuracy Radial velocity Planet Searcher (HARPS) on the 3.6 m telescope at La Silla has allowed detailed analysis of the dynamical structure of their atmospheres and close environment. The results have consequences for the calibration of the cosmic distance scale, and show that the rotation of the Milky Way is probably simpler than previously thought. However, a full understanding of the effect of spectral line asymmetries still requires the development of dedicated models.

Since Henrietta Leavitt's discovery of their unique properties in 1908 (Leavitt, 1908), the Cepheid class of pulsating supergiants has been used as a distance indicator to probe the structure of our Galaxy (Shapley, 1918) and to measure the expansion of the Universe (Hubble, 1929). When combined with velocity measurements, the properties of Cepheids are also an extremely valuable tool in investigations of just how our Galaxy, the Milky Way, rotates (Joy, 1939). Recently, the HST Key Project on the Extragalactic Distance Scale totally relied on Cepheids to calibrate far-reaching methods of distance measurement and to determine the Hubble constant (Freedman et al., 2000). However, the major uncertainty in the use of Cepheids as standard candles continues to be the accurate determination of the distance to the Large Magellanic Cloud (LMC). This distance provides the fiducial Cepheid period–luminosity relation and constitutes the largest source of uncertainty in the whole process of constructing the cosmic distance ladder.

Studying the dynamical structure of the atmospheres of Cepheids, together with their close environment, is one of the most fundamental ways to obtain constraints on the rotation of the Milky Way and to improve the distance scale ladder. In order to achieve these goals, high signal-to-noise (S/N), high spectral resolution and multi-epoch spectrographic observations of Cepheids are required.

Probing the dynamical structure of the atmospheres of Cepheids

In total, we have obtained 300 measurements using the HARPS optical spectrograph. Eight stars were observed with very high spectral and time resolution, combined with a high S/N ratio (around 300). In order to provide a dynamical picture of the pulsating atmospheres of the Cepheids, we carefully selected 17 spectral lines that are formed at different layers in the atmosphere.

The spectral line profile, in particular its asymmetry, is critically affected by how the Cepheid atmosphere pulsates and by the many phenomena involved: limb-darkening; velocity gradients within the line-forming region; turbulence; rotation; and the relative motion of the line-forming region with respect to the corresponding mass elements. When the line-forming region moves relative to the background atmospheric structure, it will also move with respect to the background velocity field. All these physical effects are also variable over the pulsation cycle.

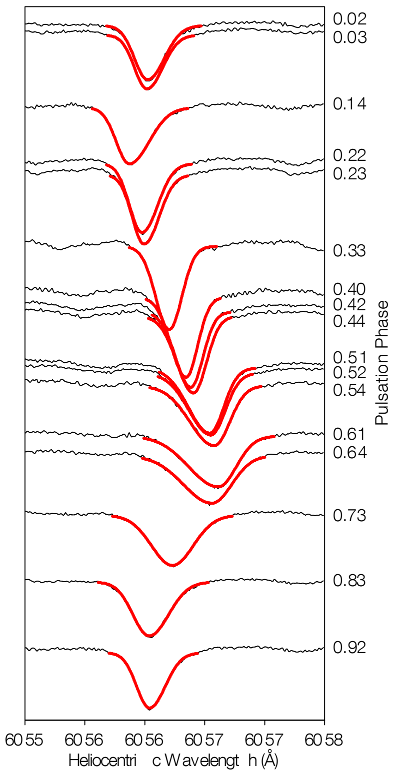

Figure 1. HARPS spectral line profiles of ß Dor (spectral resolution ≃ 120 000) together with an analytic bi-gaussian (in red) at different pulsation phases.

We extracted radial velocity and line asymmetry curves for all selected lines of all stars. Concerning the radial velocity, the best method to use — when the S/N ratio allows it — is the first moment of the spectral line profile. The radial velocity curve derived from this method is absolutely *independent* of the spectral line width and the rotation. This property is extremely valuable for comparing the behaviour of different spectral lines of different Cepheids. We also derived the spectral line asymmetries with a very high precision, using a new estimator that we called the bi-Gaussian: two analytic semi-Gaussians are actually fitted to the blue and red part of the spectral line profile respectively. The amount of asymmetry (as a percentage) is then given by the comparison of the half-width at half-maximum of each semi-Gaussian. This definition was well suited to the data quality (see Figure 1). The last very important tool we considered was the correlation curves between the radial velocities and the spectral line asymmetries (Nardetto et al., 2006).

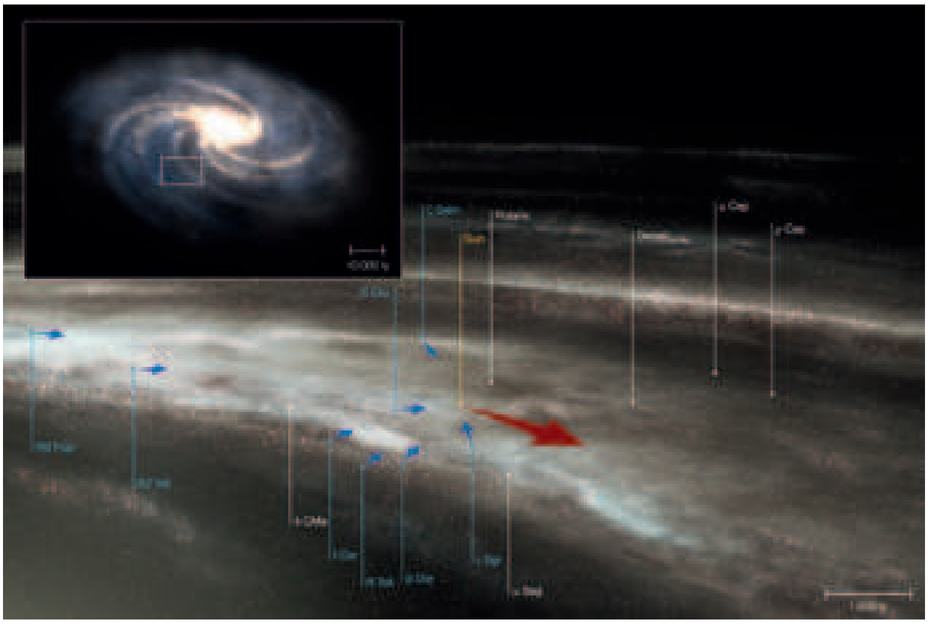

Figure 2. Artist's impression of the local neighbourhood of the Sun and its setting within our Galaxy, the Milky Way. The figure shows the positions of the eight Cepheid stars used in the investigation. After the rotation of the Milky Way had been accounted for, it seemed that the Cepheids were all 'falling' towards the Sun. New, very precise measurements with the HARPS instrument have shown that this apparent 'fall' is due to effects within the Cepheids themselves and is not related to the way the Milky Way rotates.

The rotation of the Galaxy

The motion of Milky Way Cepheids is confusing and has led to disagreement in the literature. If an axisymmetric rotation of the Galaxy is taken into account, Cepheids appear to 'fall' towards the Sun with a mean velocity of about 2 km/s (Figure 2). This residual velocity shift has been dubbed the "K-term", and was first estimated by Joy (1939) to be −3.8 km/s. Since then, the sample of stars has increased, as well as the precision of the measurements, but the problem has persisted.

A debate has raged for decades as to whether this phenomenon was truly related to the actual motion of the Cepheids and, consequently, to a complicated rotating pattern of our Galaxy, or if it was the result of effects within the atmospheres of the Cepheids.

The latest results by Pont et al. (1994) are based on an N-body simulation for the Galaxy. They ran a simulation of over 300 000 particles orbiting non-axisymmetrically about the centre of a galaxy and computed what the observed radial velocities would be from the Sun. They found a residual velocity shift of −2.1 km/s.

The measured radial velocity of a Cepheid reflects its motion in the Galaxy plus the motion of its pulsating atmosphere. The centre of mass velocity, or γ-velocity, defined as an average value of the radial velocity curve, is generally used to determine the apparent velocity of the star along the line-of-sight. While the cross-correlation method is generally used to derive the γ-velocity, we measured it independently for each spectral line of each star in our sample. Following the same definition, we measured the average values of the corresponding asymmetry curves, which we called the γ-asymmetries (Figures 3a and 3b). Interestingly, for each Cepheid in our sample, we found a linear relation between the γ-velocities of the various spectral lines and their corresponding γ-asymmetries. This result is actually easily understandable: the more asymmetric the line, the larger the first moment of the spectral line (as an absolute value). It also shows that the residual γ-velocities stem from the intrinsic properties of Cepheids.

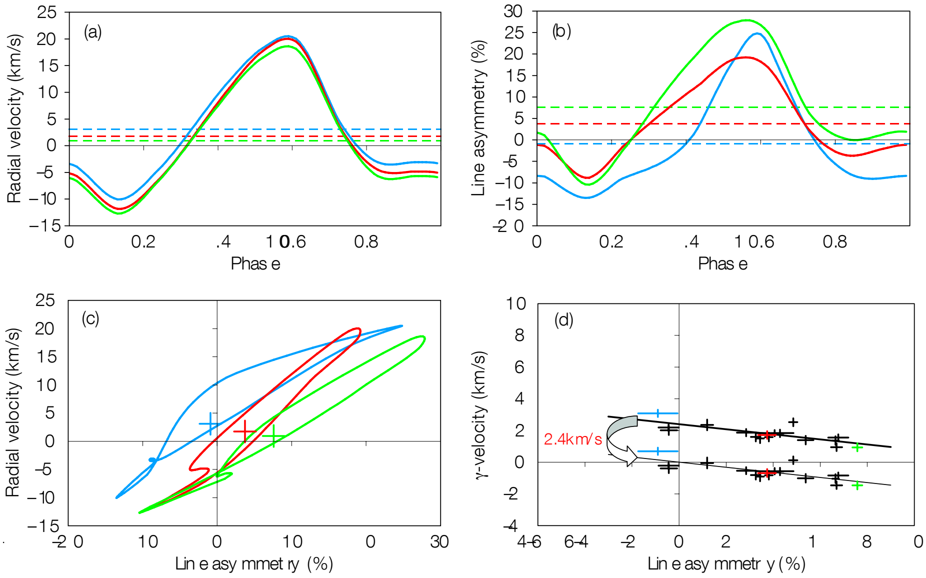

Figure 3. Radial velocities (a) and line asymmetries (b) are presented as a function of the pulsation phase for three spectral lines for the case of ß Dor: (Fe I 489.6 nm [blue line]; Fe I 537.3 nm [red line]; Fe I 602.4 nm [green line]). Horizontal dashed lines correspond to the average values of the interpolated curves, respectively. In (c) velocity as a function of the line asymmetry, and the corresponding (γ-asymmetry, γ-velocity) average values (crosses) are shown for the three different lines. In (d) a generalisation of diagram (c) is shown for all spectral lines. The velocity-versus-asymmetry plots are not included for clarity. The upper values are without any correction except for the Galactic Cepheid Database γ-velocity. The origin of the plot is then used as a physical reference for all spectral line γ-velocities of the star (lower values). We find a correction of −2.4 km/s for ß Dor that is consistent with the K-term value.

Using these linear relations, we can provide a physical reference to derive the centre of mass velocity of our stars: it should be zero when the γ-asymmetry is zero (Figures 3c and 3d). The corrections we found between our 'calibrated' velocities and the ones found in the literature (from the Galactic Cepheid Database [1]), range from –0.2 to –3.6 km/s. The average value (over the eight Cepheids) is –1.8 ± 0.2 km/s, which is consistent with the K-term value.

Our observations show that this apparent motion towards us almost certainly stems from an intrinsic property of Cepheids.

This result, if generalised to all Cepheids, implies that the rotation of the Milky Way is simpler than previously thought, and is certainly axisymmetric (Nardetto et al., 2008a).

The γ-asymmetries of spectral lines also show a trend with the period of the star. We investigated several physical explanations for these non-zero γ-asymmetries, such as velocity gradients or the relative motion of the line-forming region compared to the corresponding mass elements. However, none of these hypotheses seems to be entirely satisfactory to explain the observations. Further numerical investigations are required.

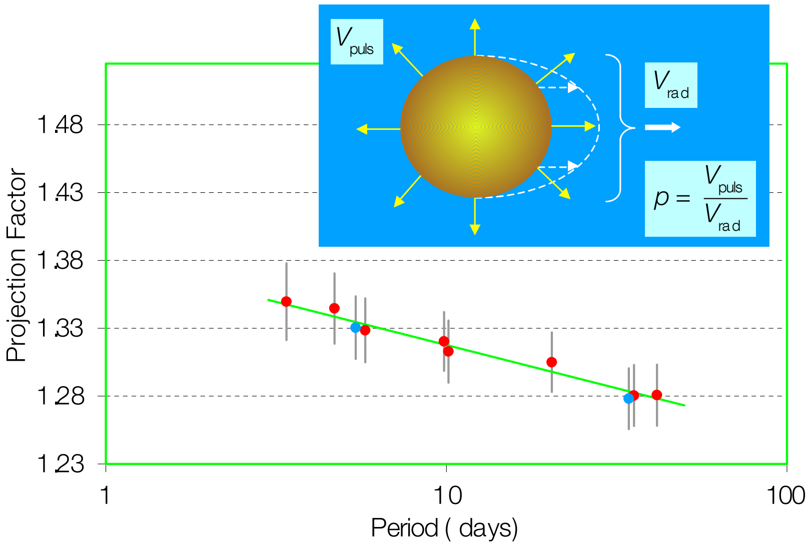

Figure 4. The projection factor (p) used in the interferometric Baade-Wesselink (IBW) and infrared surface brightness (IRSB) methods for determining the distance of Cepheids includes a geometrical effect (see inset box), a velocity gradient within the atmosphere and the relative motion of the line-forming region with respect to the corresponding mass elements. A relation was found between the projection factor and the logarithm of the period. Red points are semi-theoretical (including the HARPS determination of velocity gradients), while blue points are from hydrodynamical models.

The distance scale calibration

Two methods have recently been used to calibrate the period–luminosity relationship for determining the distance of Cepheids (see, e.g., Kervella et al., 2004): the infrared surface brightness method (IRSB); and the interferometric Baade-Wesselink (IBW) method. The basic principle behind these two methods is to compare the linear and angular size variation amplitudes of a pulsating star to derive its distance through a simple division. The *caveat* is that interferometric or photometric measurements in the continuum lead to angular diameters corresponding to the photospheric layer, while the linear stellar radius variation is deduced from spectroscopy, i.e., it is based on line-forming regions that are formed at high altitudes above the photosphere. Thus, radial velocities V_{rad}, which are derived from line profiles, include the integration in two directions: over the stellar surface (weighted by the limb-darkening effect), and over the atmospheric layers (through velocity gradients in the thickness of the atmosphere). All these phenomena are currently merged into one parameter, generally considered as constant with time: the projection factor p, defined as $V_{puls} = pV_{rad}$, where V_{puls} is defined as the photospheric pulsation velocity. Then V_{puls} is integrated with time to derive the photospheric radius variation. The precision in the distance currently obtained with the IBW and IRSB methods is a few percent; however, they remain strongly dependent on the projection factor.

Based on hydrodynamical models for δ Cep and *l* Car, we devised a new spectroscopic method of determining the projection factor. This method was then applied to the stars observed with the HARPS spectrometer. We divide the projection factor into three sub-concepts: (1) a geometrical effect; (2) the velocity gradient within the atmosphere; and (3) the relative motion of the 'optical' pulsating photosphere compared to the corresponding mass elements. Both (1) and (3) are deduced from geometrical and hydrodynamical models, respectively, while (2) is derived directly from spectroscopic observations by considering different lines that are formed at different layers in the atmosphere, allowing us to measure velocity gradients. We found, for the first time, a period–projection factor relation P_p (Figure 4). This P_p relation is an important tool for removing a bias in the calibration of the period–luminosity relation of Cepheids. We emphasise that if a constant projection factor is used (generally $p = 1.36$ for all stars) to derive the period–luminosity relation, errors of 0.10 on the slope and 0.03 magnitude on the zero-point of the period–luminosity relation can be introduced (Nardetto et al., 2007). Our semi-theoretical P_p relation has been confirmed by Hubble Space Telescope (HST) observations (Mérand et al., 2005; Fouqué et al., 2007).

Using this P_p relation in the IBW and IRSB methods of distance determination, as well as HST parallaxes, Fouqué et al. (2007) showed that the slope of the Galactic and LMC period–luminosity relations are similar. This result shows that applying the well-determined LMC slopes

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[1] *http://www.astro.utoronto.ca/DDO/research/cepheids/*

to distant galaxies of different metallicities is warranted. However, metallicity effects are not excluded concerning the zero-point of the period–luminosity relations, which still prevents us from determining the distance to the LMC directly. Using the IBW and IRSB methods, our group expects to determine the distance of 20 Galactic Cepheids with a precision of 2 % in the near future, and to calibrate the Galactic period–luminosity relation with an error of less than 0.01 magnitude. Work in progress shows that a good precision can be also obtained on the distance of LMC Cepheids using the IRSB method. An accuracy on the distance modulus of the LMC of 0.01 magnitude and 5 % on the Hubble constant are now conceivable.

The close environment of Cepheids

Another possible bias in the IBW and IRSB methods of determining the distance of Cepheids is the presence of a circumstellar envelope, which has been recently discovered by Kervella et al. (2006) and Mérand et al. (2007). Such envelopes have a signature in the Hα line profiles.

The Hα line profiles were described for all stars using a 2-D (wavelength versus pulsation phase) representation. For each star, an average spectral line profile was derived, together with its first moment (γ-velocity) and its asymmetry (γ-asymmetry). Short period Cepheids show Hα line profiles which closely follow the pulsating envelope of the star, while long period Cepheids show very complex line profiles and, in particular, large asymmetries (Figure 5). We also confirmed a dominant absorption component with a constant, almost-zero velocity in the stellar rest frame for *l* Car. This component is attributed to the presence of a circumstellar envelope. For other Cepheids, the central component is certainly too faint to be observed in our spectra.

Interestingly, we found a new relationship between the period of Cepheids and their Hα γ-velocities and γ-asymmetries. However, regarding the metallic lines, the γ-asymmetries of metallic lines are a few percent and show a decrease with the period of the Cepheid. In comparison, γ-asymmetries measured for the Hα line profiles increase with the period and reach about 20 % for long period Cepheids. Therefore, we suggest that γ-asymmetries (or γ-velocities) corresponding to metallic and Hα lines are the result of different physical mechanisms. Even if the γ-velocities of Hα line profiles might be partially due to the dynamical structure of the Cepheid atmosphere, it seems reasonable to also invoke some possible mass loss from Cepheids with typical velocities projected on the line of sight up to –20 km/s (Nardetto et al., 2008b). The most spectacular example of circumstellar material around a Cepheid is the large light-scattering nebula of the long period Cepheid RS Pup (Kervella et al., 2008). Moreover, strong pulsational compression of atmospheric layers and shock waves have been observed in the short period Cepheid X Sgr (Mathias et al., 2006), a star that is also part of our HARPS sample, as well as RS Pup.

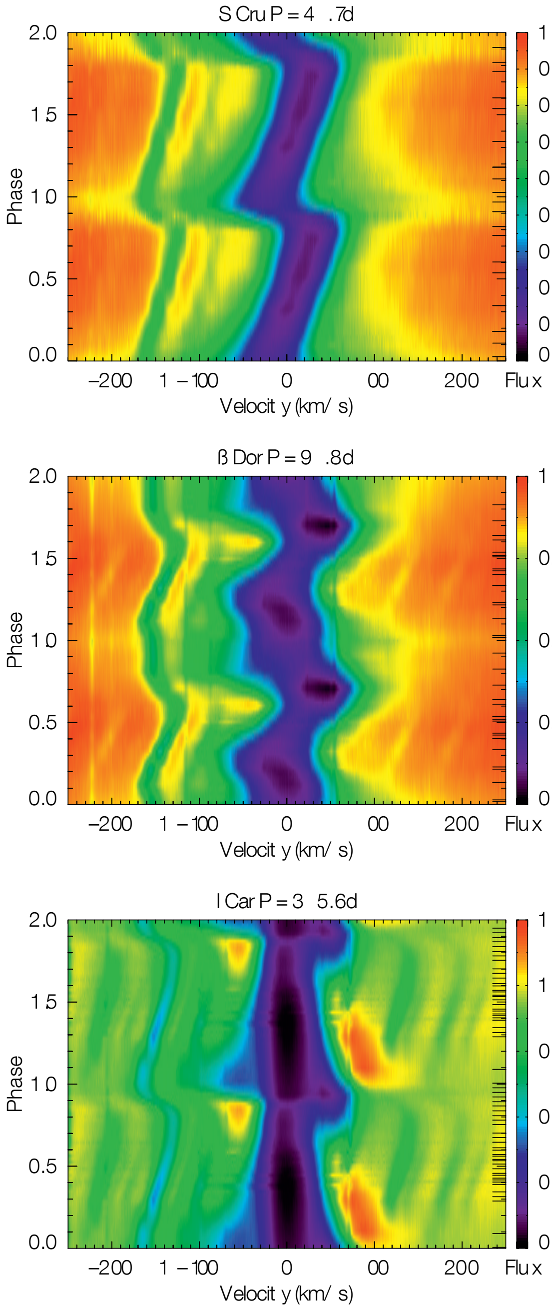

Figure 5. Hα line profiles of short, medium and long period Cepheids. Time series of HARPS spectra are interpolated to provide a two-dimensional map of the Hα profile in the [–250, 250] km/s velocity range. Diagrams are given in the stellar rest frame with positive velocities corresponding to receding motion (redshifted). The pulsation phase is indicated on the left edge of each panel and on the right we quote the pulsation phases corresponding to our observations (data are duplicated over two pulsation cycles for clarity). For each star the colour bar indicates the continuum-normalised flux.

Prospects

While we found that the rotation of the Milky Way is likely to be simpler than previously thought, the dynamical structure of a Cepheid atmosphere is conversely much more complex than their radial pulsation would indicate. For a better understanding of the γ-asymmetries, we gathered high resolution infrared spectra with VLT/CRIRES in order to sample different line-forming regions in the Cepheid atmospheres. Another very promising instrument is VEGA: a visible spetrograph and polarimeter mounted on the Center for High Angular Resolution Astronomy (CHARA) interferometer. As it combines very high spectral resolution (R = 30000) and high angular resolution (sub-milliarcsecond) at visible wavelengths, VEGA will provide novel geometrical constraints on the dynamics of Cepheids. Further insights into the link between γ-asymmetries and atmosphere dynamics will also come from the application of our data analysis techniques to other classes of pulsating stars (such as RR Lyr, δ Scu, etc.).

Although the hydrodynamical code for pulsating stars that we are using (Fokin, 1991) reproduces the atmospheric velocity gradients extremely well and provides spectroscopic and spectro-interferometric observables, it is not capable of describing very subtle and second order physical behaviour, like γ-asymmetries. Therefore, further numerical studies are required to investigate the effect of convective flows and complex radiative transport on the atmospheres of Cepheids. These phenomena, as well as mass loss, the circumstellar envelope, and the exact evolutionary state of the star, have to be incorporated simultaneously and consistently into dedicated numerical models to reproduce the observed spectral line profiles in detail.

A better understanding of the atmospheric dynamics of Cepheids has already given us a better understanding of the rotation of our Galaxy. It represents key progress towards a truly accurate calibration of their distance scale. Exactly a century after the discovery of the period–luminosity relation (Leavitt, 1908), the pulsation mechanism of Cepheids is still a challenge to understand today, and high resolution spectra are certainly part of the key.

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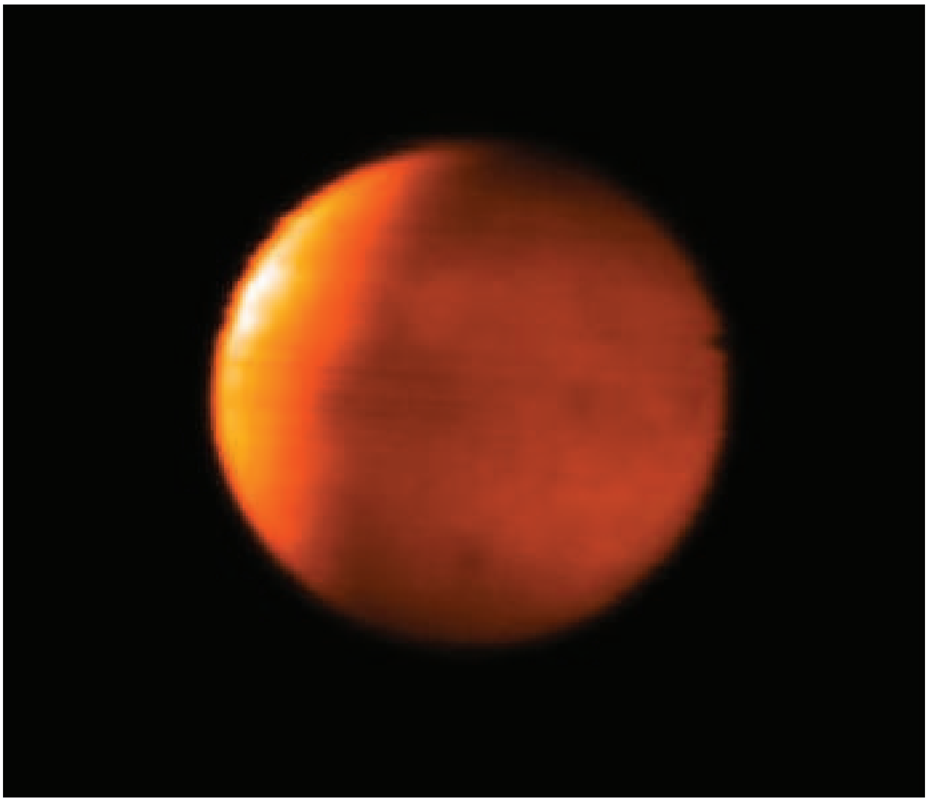

The Moon at 3 mm wavelength. The data used to produce this image were taken with the European ALMA prototype antenna as part of a test of the continuum raster map observing mode at the ALMA Test Facility in August 2008. The data acquisition and reduction were all performed with the ALMA software that is being prepared for use next year for commissioning of the real ALMA hardware in Chile.