Improving the Cepheid Distance Scale

Lucas Macri

The Cepheid Period-Luminosity Relation is one of the most widely used distance indicators. In the 1990s, the Hubble Space Telescope (HST) was used to discover Cepheid variables in more than 30 galaxies, some as far away as 20 Mpc. The aim of those observations was to calibrate a slew of secondary distance indicators to measure the Hubble Constant. The HST Key Project on the Extragalactic Distance Scale (Freedman et al. 2001) estimated the uncertainty in their determination of H_0 to be 10%.

That uncertainty is largely dominated by two systematic terms: the absolute distance to the Large Magellanic Cloud (LMC), which serves as the “first rung” in the Cepheid Distance Scale; and possible changes in Cepheid luminosities and effective temperatures as a function of their metal content, commonly referred to as the “metallicity effect.” Recently, the results announced by the Wilkinson Microwave Anisotropy Probe team (Spergel et al. 2003) have emphasized the need for a determination of H_0 accurate at the 5% level or better to provide independent constraints on the equation of state of dark energy. Improvements in the Cepheid Distance Scale are needed to meet that challenge.

The distance to the LMC has been the subject of intense debate for several decades, and will likely be determined to 1–2% through observations of detached eclipsing binaries being carried out with HST and the CTIO 4-m telescope (Fitzpatrick et al. 2003; Ribas et al. 2002). The metallicity effect arises because the Cepheids in the LMC have a markedly lower metal content ($Z=0.008$) than the Cepheids discovered with HST in distant spiral galaxies (averaging $Z=0.02$).

There have been several observational estimates of the amplitude of the metallicity effect over the past decade (Kennicutt et al. 1998; Kochanek 1997; Sasselov et al. 1997). These studies found that the metallicity effect would result in an underestimate of the true distance to a galaxy whose Cepheids are richer in metals than the LMC. However, theoretical studies (Bono et al. 1999; Fiorentino et al. 2002) have claimed the opposite sign for the effect. The discrepancy between the theoretically predicted correction and the one adopted by the HST Key Project on the Extragalactic Distance Scale (Freedman et al. 2001) amounts to a 15% difference for solar-metallicity variables.

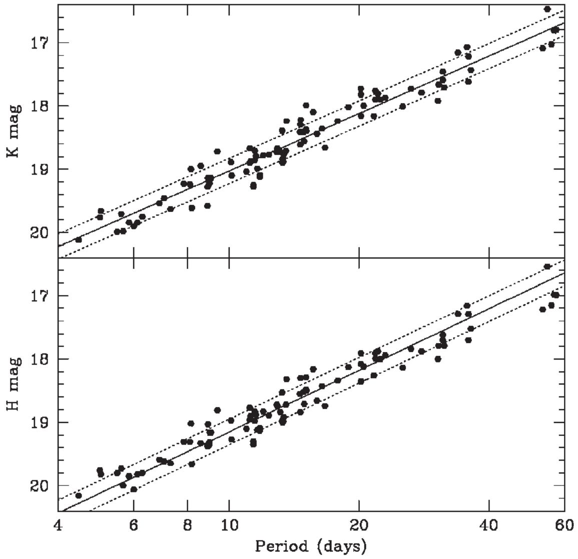

Figure 1. One of the eleven Gemini fields observed with NIRI, overlaid on a BVI mosaic of the center of M33. Created from data taken at WIYN.

The Local Group galaxy Messier 33 is an ideal laboratory in which to characterize the metallicity dependence, since its abundance gradient is one of the largest among nearby spirals: 0.2 dex/kpc (Henry and Howard 1995; Monteverde et al. 2000). The DIRECT Project, led by K. Z. Stanek of the Harvard-Smithsonian Center for Astrophysics, carried out a synoptic survey of M31 and M33 over 170 nights from 1996 to 1999 using the Fred L. Whipple Observatory 1.2-m telescope on Mount Hopkins, AZ. More than 350 Cepheids were discovered in the central part of M33 (Macri et al. 2001), and a similar number are expected to be found in the outer regions of the galaxy. The variables span a range in abundance from solar to sub-LMC, which will allow a clear measurement of the metallicity effect.

During the 2002B semester, follow-up observations of the DIRECT Cepheids were conducted in the optical (*BVI*) and near-infrared (HK_S), using the WIYN 3.5-m telescope with MiniMosaic and the Gemini North 8-m telescope with NIRI, respectively. The excellent seeing provided by WIYN (0.75 arcsec) will allow a robust absolute calibration of the original DIRECT survey data in the *B*, *V* and *I* bands, and will yield high-quality light curves that can be used to reject unresolved blends of Cepheids with other disk stars. The Gemini data

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will allow a significant increase in the wavelength coverage of the variables, which is crucial to separate the effects of interstellar absorption from those due to the metallicity effect. Figure 1 shows one of 11 Gemini fields overlaid on a *BVI* mosaic of the center of M33 created from our WIYN observations. The results of the Gemini observations are shown in figure 2. Thanks to a median seeing of 0.35 arcsec and the large aperture of the telescope, eleven fields were observed using only six hours of telescope time, resulting in the detection of close to 100 Cepheids with periods ranging from 4 to 60 days.

Additional WIYN and Gemini observations, proposed for the 2003B semester, will complete this project.

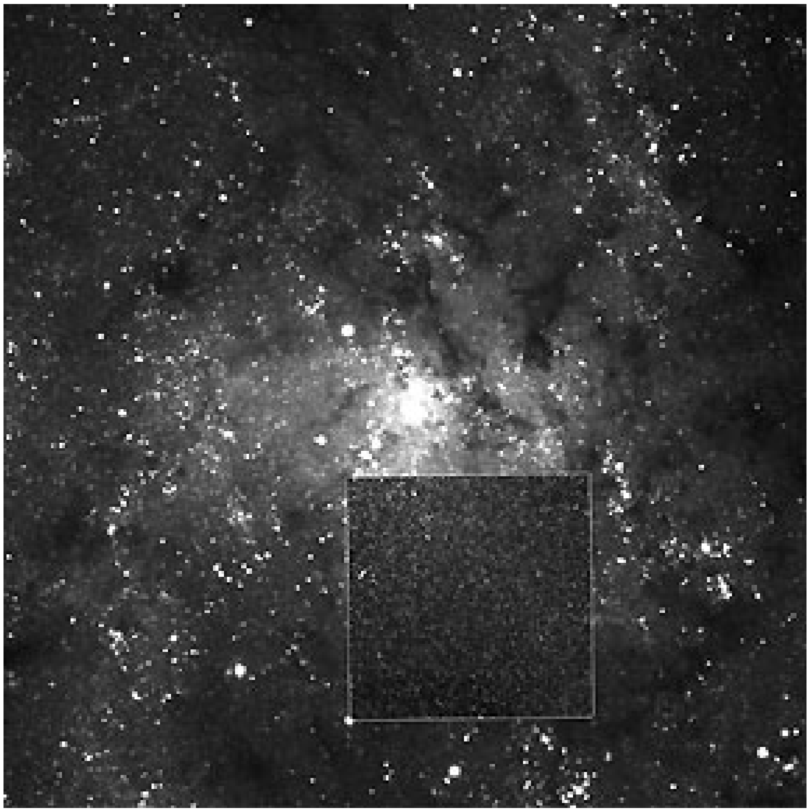

Figure 2. Period-magnitude relation for M33 Cepheids detected with NIRI on Gemini North. These data will be used to improve the Cepheid distance scale and may ultimately play a role in constraining the equation of state of dark energy.

What Sets the Initial Angular Momentum of a Star?

Based on a contribution solicited from Sidney C. Wolff

Why do stars rotate so slowly? Recent theories of star formation assume that stars acquire a significant fraction of their final mass by rapid accretion through disks. Stars that form in this way should be rotating at nearly breakup speed. However, the typical rotational velocities of the youngest stars instead fall a factor of five or more below this critical velocity. The low observed velocities have been explained by positing that stars are locked to their surrounding disks via magnetic fields and that the disk applies a braking torque. Does this model work quantitatively?

A recent study by Sidney C. Wolff and Stephen Strom (NOAO) and Lynne Hillenbrand (Caltech) suggests that disk locking may indeed explain the initial angular momenta of stars. As described by Wolff and colleagues, if protostars accrete most of their mass on a time scale that is short compared to the time scale for contraction, then stars initially appear high on their convective tracks, on a locus known as the stellar "birthline." Assuming that stars remain locked to their disks as they accrete up the birthline, the specific angular momentum (J/M) of a star of mass (M) is $J/M = [I\varepsilon(GM)^{5/7}(2)^{3/14}\dot{M}^{3/7}](M\beta^{3/2}B^{6/7}R^{18/7})$, where I is the stellar moment of inertia, $\dot{M}$ is the mass accretion rate, B is the magnetic field strength, and R is the stellar radius (Königl 1991). The constants ε and β are less than or equal to 1. Wolff and colleagues propose that given a mass-radius relationship for the birthline, an assumed magnetic field strength of 2500 gauss, which is typical of the measured values for T Tauri stars, and an accretion rate that varies as

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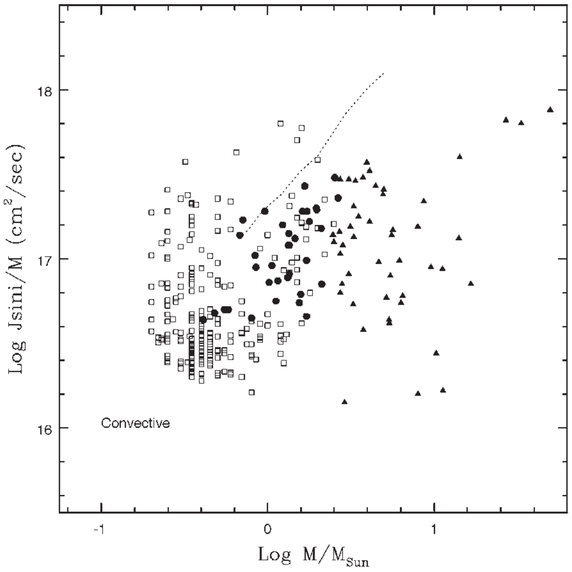
Angular Momentum continued

$10^{-5} M^{1.5}$ solar masses per year (Behrend and Maeder 2001), the initial specific angular momentum can be determined as a function of mass (see figure). The relation above also suggests that a range of rotation rates will be observed if there are variations from star to star in the magnetic field strength or accretion rate.

To see whether this picture can account for the initial rotation rates of stars, Wolff and colleagues observed a sample of pre-main sequence stars in Orion. Measurements of the rotational velocity (*v*sin*i*), obtained from spectra taken at the WIYN telescope in 1992, were used to calculate the projected angular momentum (*J*sin*i*). Markedly different distributions of stellar angular momentum were found for stars on convective tracks, as compared to those on radiative tracks. The results for stars on convective tracks are shown in the figure. The upper bound of the observed values of *J*sin*i*/*M* increases slowly from 0.1 to 10 solar masses. As shown in the figure, the very simple scaling described above yields predicted rotation rates that are remarkably close to the observed values. Wolff concluded, "Disk-locking does indeed offer a plausible explanation for the initial rotation rates of stars."

The results of this study also suggest that stars lose significant amounts of their initial angular momenta as they evolve down their convective tracks. For example, the specific angular momentum distribution found for stars on convective tracks differs from that of main sequence stars. Main sequence stars follow a similar power law for masses greater than two solar masses, but stars with masses less than two solar masses rotate much more slowly than the extension of the power law would predict. Wolff and colleagues found that a similar break in the angular momentum distribution is already present in the population of Orion stars on radiative tracks, indicating that a substantial loss of angular momentum occurs as stars evolve down their convective tracks. Whether disk locking can also explain angular momentum loss in this phase of evolution is an open question.



Specific angular momentum as a function of mass for stars on pre-main sequence convective tracks. Filled circles represent Orion stars observed in the study by Wolff, Strom, and Hillenbrand. The lower-mass stars studied by K. L. Rhode, W. Herbst, and R. D. Mathieu (2001) are also shown (open squares). Filled triangles represent Orion stars with T_{eff}>10,000 K, which are already on the main sequence. Predicted values of J/M along the birthline are indicated by the dotted line.

Low-Mass Stars Pair Up Too Often

Based on a contribution solicited from Laird Close (Steward Observatory, University of Arizona)

A new study of binarity at the bottom of the main sequence has yielded new insights into the formation of low-mass stars and brown dwarfs. Using the Hokupa'a Adaptive Optics system on the Gemini North telescope, Laird Close and graduate students Nick Siegler, Melanie Freed, and Beth Biller of Steward Observatory (University of Arizona) have searched for companions to the lowest-mass stars in the solar neighborhood, objects with masses in the range 75–95 Jupiter masses.

Over several nights during which the seeing was excellent (~0.5 arcsec at *R*), Close and colleagues imaged the immediate environs of 39 nearby objects with spectral types M8 to L0.5. The targets, selected primarily from the 2MASS results of Gizis et al. (2002), were imaged at ~0.1 arcsec resolution at *J*, *H*, and *K′*. To achieve this angular resolution, Close and colleagues capitalized on the photon-counting sensitivity of the curvature wavefront sensor (WFS) on Hokupa'a to guide on the extremely faint

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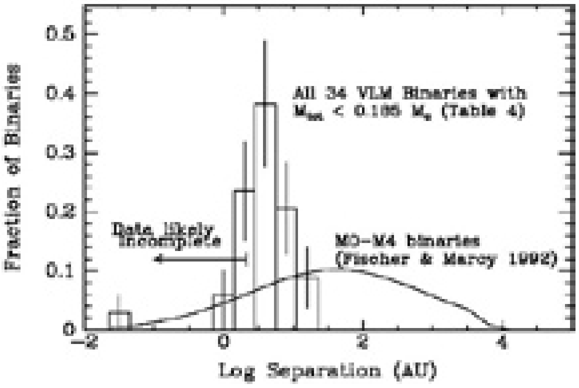
Low Mass Stars continued



Binary fraction as a function of orbital separation for the 34 known very low-mass binaries (histogram). The distribution of separations for M0–M4 binaries (Fischer and Marcy 1992) is also shown. In comparison, the very low-mass binaries appear to be in much tighter orbits.

(*I*~17–18) primary stars. Commenting on this aspect of their project, Close remarked, "This is really quite a significant feat since these objects are so cool (T_{eff} ~2,400–2,600 K) that the WFS was only receiving ~4 photons per sample (*V*~18.5 mag). Hence it was impressive that Hokupa'a was able to produce 0.1 arcsec images at *K´* even at such a low photon rate." The resulting observations represent the largest survey of M8–L0.5 stars at this angular resolution. The results of the study have appeared in the April 10 issue of the *Astrophysical Journal* (Close et al. 2003).

Close and colleagues found that 9 of the 39 objects in the sample were binary systems. The companions to such low-mass stars are themselves either on or below the stellar-brown dwarf boundary. Indeed the companions to 2M2331 and LHS2397a are more than two magnitudes fainter than their primaries and have spectral types of L7–L8. Thus, they are certainly brown dwarfs (Freed, Close, and Siegler 2003).

The results of the survey show that very low-mass binaries are rarer, more nearly equal mass, and much more tightly bound compared to binaries with more massive primaries. All of the detected companions were found to have separations less than 15 AU. In fact, among all 34 of the low-mass/brown dwarf binaries known, none have separations greater than 15 AU (see figure). The peak in the separation distance for very low mass binaries is ~4 AU. In contrast, the more massive M0–M4 binaries have a separation distribution that peaks much further out at ~30 AU. The volume-limited binary frequency of the survey was 15±7% for systems with separations >3 AU. In contrast, 32±9% of the more massive M0–M4 stars have companions with separations >3 AU. Hence, it appears that low-mass binaries have half the binary fraction of stars only slightly more massive.

Although a binary fraction of 15% is low compared to the binary fraction of more massive stars, it is still a surprisingly high number. Current star-formation models predict a much lower fraction of binaries for such low-mass stars. Most theories predict that low-mass objects are ejected early in the star formation process. As a result, only a small fraction of very low mass binaries are expected to survive the ejection process (<5%). "There is currently an active effort to try and produce a single model that predicts the binary fraction for both low-mass and high-mass stars self-consistently," Close says. "Until that occurs, it is clear that there is some interesting physics to star formation that we do not yet fully understand."

In addition to testing theories of the formation of low-mass objects, the binary systems discovered in the survey can be used to improve our understanding of fundamental properties of stars. For example, since the expected orbital period of these systems is short (15 to 20 years), these binary systems may play a critical role in the calibration of the mass-luminosity-age relation for low-mass stars and brown dwarfs.

Infrared Molecular Lines Reveal Rapid Outflow in Sunspot Penumbral Fibrils

Matt Penn & Bill Livingston (NSO), Wenda Cao (NJIT/Yunnan Observatory),
Steve Walton & Gary Chapman (California State Northridge)

The Evershed effect is a horizontal outflow of plasma from the inner region of a sunspot toward the quiet Sun and is observed in the penumbra of sunspots. Spectroscopic observations of the Evershed flow use the fact that the mainly horizontal flow, when observed in sunspots near the edge of the Sun, produces a line-of-sight Doppler shift due to the geometric projection involved. Observations of lines from neutral atoms, particularly Fe, show a more complicated situation, however, producing line asymmetries rather than simple Doppler shifts, due to seeing effects and the formation properties of the spectral line in the solar atmosphere.

New observations of the Evershed flow using a CN molecular absorption line at 1564.6 nm reveal a different situation. Since the CN line is formed only in the cool temperatures found in the dark penumbral fibrils, the spectroscopic properties of the line will only reflect the physical conditions present in the dark fibrils, independent of seeing or other spatial averaging. Measurements were made of several sunspots using the NSO-California State Northridge infrared (IR) camera and spectropolarimeter during June 2002 at the McMath-Pierce telescope. To improve the spectral signal-to-noise of the data, a plane-polar coordinate system was calculated (see figure 1) and the raw spectra were averaged into 16 azimuthal bins (using about 300 raw spectra per bin). The spectra were then plotted as a function of azimuthal angle, and the Doppler signature of an outflow was readily apparent. Observations of sunspot NOAA 10008 on three days show Evershed outflows as a Doppler shift of the CN line, with a typical velocity of 6 km/sec (see figure 2). A similar behavior was seen with spectral lines at 2231 nm. A temperature-sensitive Ti line and an unidentified molecular line (which shows a temperature dependence similar to CN) exhibited similar characteristic outflows. The polarimetric observations of the Ti line implied a mean penumbral magnetic field of 1400 gauss in these outflow regions.

This work has been accepted by the *Astrophysical Journal.*

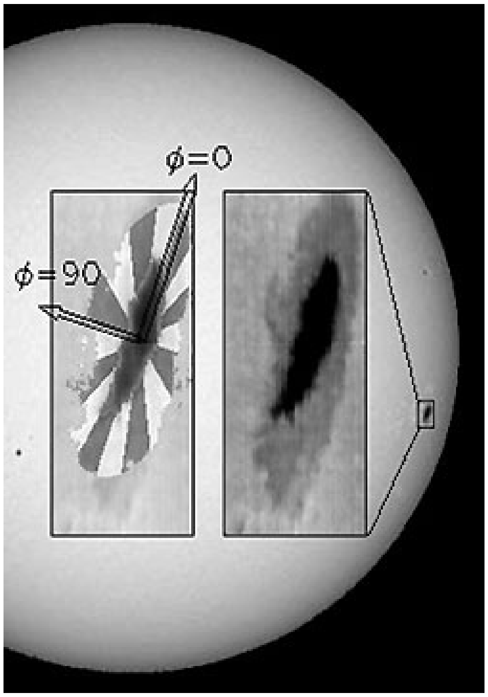


Figure 1. Background image from the NSO Kitt Peak Vacuum Telescope at 869 nm showing the disk position of NOAA 10008 on 29 June 2002. The two inset images show continuum maps of the spot region, with the penumbral bins and spot azimuth directions shown in the left inset. The penumbral spectra were binned in 16 azimuthal bins. An azimuth of 90 degrees is defined as toward the center of the solar disk.

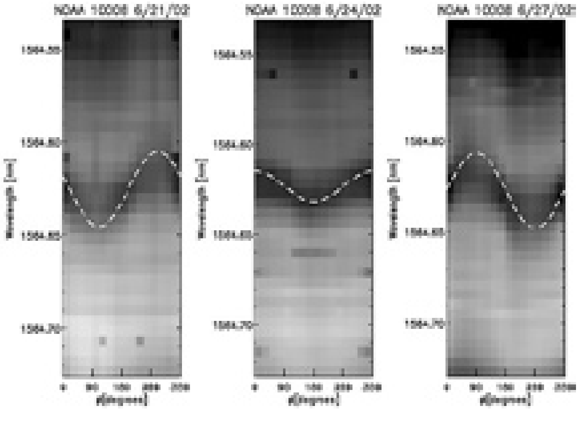


Figure 2. The CN line at 1564.6 nm showing a Doppler shift as a function of azimuth angle around the sunspot NOAA 10008 during three days. The spot positions were 0.65 (east), 0.27 and 0.66 (west) solar radii from disk center on June 21, 24, and 27, respectively. The line absorption can be seen at a variety of wavelengths ranging from zero outflow speed up to about 9 km/sec. The dashed lines show the typical horizontal speed of 6 km/sec corrected for projection effects.