Microlensing and the Physics of Stellar Atmospheres

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Abstract. The simple physics of microlensing provides a well-understood tool with which to probe the atmospheres of distant stars in the Galaxy and Local Group with high magnification and resolution. Recent results in measuring stellar surface structure through broad band photometry and spectroscopy of high amplification microlensing events are reviewed, with emphasis on the dramatic expectations for future contributions of microlensing to the field of stellar atmospheres.

1. Introduction

The physics of microlensing is simple. For most current applications, the principles of geometric optics combined with one relation (for the deflection angle) from General Relativity is all that is required. For observed Galactic microlensing events, the distances between source, lens and observer are large compared to intralens distances, so that small angle approximations are valid. Although it is possible that most lenses may be multiple, $\sim$90% of observed Galactic microlensing light curves can be modeled as being due to a single point lens. Usually, though not always (cf., Albrow et al. 2000), binary lenses can be considered static throughout the duration of the event.

The magnification gradient near caustics is large, producing a sharply peaked lensing "beam" that sweeps across the source due to the relative motion between the lens and the sight line to the source (Fig. 1). Furthermore, the combined magnification of the multiple microimages (which are too close to be resolved with current techniques) is a known function of source position that is always greater than unity, so that more flux is received from the source during the lensing event. The net result is a well-understood astrophysical tool that can simultaneously deliver high resolution and high magnification of tiny background sources. In Galactic microlensing, these sources are stars at distances of a few to a few tens of kiloparsecs.

The great potential of microlensing for the study of stellar polarization (Simmons, Willis, & Newsam 1995; Simmons, Newsam & Willis 1995; Newsam et al. 1998; Gray 2000), stellar spots (Heyrovský & Sasselov 2000; Bryce & Hendry 2000), and motion in circumstellar envelopes (Ignace & Hendry 1999) will not be treated here. Instead, the focus will be on how the composition of spherically-symmetric stellar atmospheres can be probed by microlensing.

Figure 1.   **Left:** The trajectory of the background source star passed over a caustic curve cusp of the binary lens MACHO 97-BLG-28. Units are θ_{E}. **Right:** The fractional (magnified) flux in 10 concentric rings of equal area over the stellar disk are shown as a function of time during the two-day crossing (Albrow et al. 1999a).

2.   Caustic Transits

The angular radius θ_{E} of a typical Einstein ring is about two orders of magnitude larger than the size θ_* of a typical Galactic source star (few μas), but the gradients in magnification that generate source resolution effects are appreciable only in regions near caustics. For a single point lens, the caustic is a single point coincident with the position of the lens on the sky that must directly transit the background source in order to create a sizable finite source effect. The probability of such a point transit is of order $\rho \equiv \theta_*/\theta_{\mathrm{E}} \approx 2\%$. The amount of resolving power will depend on the dimensionless impact parameter β, the distance of the source center from the point caustic in units of θ_{E}. The first clear point caustic transit was observed in event MACHO 95-BLG-30 (Alcock et al. 1997).

Lensing stellar binaries with mass ratios $0.1 \lesssim q \equiv m_2/m_1 \lesssim 1$ and separations $0.6 \lesssim d \equiv \theta_{\mathrm{sep}}/\theta_{\mathrm{E}} \lesssim 1.6$ generate extended caustic structures that cover a sizable fraction of the Einstein ring (see, eg., Gould 2000). Since events generally are not alerted unless the source lies inside the Einstein ring, any alerted binary event with q and d in these ranges is highly likely to result in a caustic crossing. If the source crosses the caustic at a position at which the derivative of the caustic curve is discontinuous, it is said to have been transited by a cusp. For a given lensing binary, the probability of a cusp transit is of order $\rho\, N_{\mathrm{cusps}} \approx 10\%$. Since $\sim 10\%$ of all events are observed to be lensing stellar binaries, the total cusp-transit probability is $\sim 1\%$. To date, two cusp-crossing events have been observed, MACHO 97-BLG-28 (Albrow et al. 1999a) and MACHO 97-BLG-41 (Albrow et al. 2000). The remaining caustic crossing are transits of simple fold (line) caustics, which are observed in $\lesssim 10\%$ of all events. Caustics thus present a non-negligible cross section to background stellar sources, with fold caustic transits being most likely by a factor of ~ 5.

Figure 2. **Top:** The *V*- and *I*-band light curves of MACHO 97-BLG-28 plummet as the trailing limb of the source exits the caustic. **Bottom:** Residuals (in magnitudes) from the best models using a uniformly-bright (right) and limb-darkened (left) stellar disk. The same models are superposed on the light curves (Albrow et al. 1999a). The varying scatter reflects different conditions at the three telescopes.

The largest effect of a caustic crossing over an extended source is a broadening and diminishment of the light curve peak at transit that depends on the finite size ($\rho \neq 0$) of the source. If the angular size θ_* of the source star can be estimated independently (eg., from color-surface brightness relations), then the time required for the source to travel its own radius, and thus its proper motion μ relative to the lens, can be determined from the light curve shape. Conversely, unless an independent method is available (see, Han 2000) to measure μ or θ_E, photometric microlensing cannot translate knowledge of the dimensional parameter ρ into a measurement of source radius. What photometric or spectroscopic data alone *can* yield is a characterization of how the source profile differs from that of a uniform disk (Fig. 2). Microlensing has already yielded such information for stars as distant as the Galactic Bulge and Small Magellanic Cloud.

3. Recent Contributions of Microlensing to Stellar Physics

The potential to recover profiles of stellar atmospheres from microlensing has been recognized for several years (Bogdanov & Cherepashchuk 1995; Loeb &

Figure 3.   Stellar profiles deduced from microlensing light curve data (bold lines) and from atmospheric models (dashed lines) for the K-giant source star of MACHO 97-BLG-28 (Albrow et al. 1999a).

Sasselov 1995; Valls-Gabaud 1995), but made possible only recently, due to the improved photometry and especially temporal sampling now obtained for a large number of events by worldwide monitoring networks. For only a few stars, most of which are supergiants or very nearby, has limb darkening been observationally determined by any technique. Microlensing has the advantage that: (1) many types of stars can be studied, including those quite distant; (2) the probe is decoupled from the source; (3) the signal is amplified (not eclipsed); and (4) intensive observations need only occur over one night.

3.1.   Limb Darkening

The first cusp crossing was observed in MACHO 97-BLG-28, and led to the first limb-darkening measurement of a Galactic Bulge star (Albrow et al 1999a). As the source crossed the caustic cusp, a characteristic anomalous bump was generated in the otherwise smooth light curve. First the leading limb, then the center, and finally the trailing limb of the stellar disk were differentially magnified (Fig. 1). Analysis of the light curve shape during the limb crossing allowed departures from a uniformly-bright stellar disk to be quantified (Fig. 2) and translated into a surface brightness profile in the V and I passbands. A two-parameter limb-darkened model provided a marginally better fit than a linear model. Spectra provided an independent typing of the source as a KIII giant. The stellar profile reconstructed from the microlensing light curve alone is in good agreement with those from stellar atmosphere models (van Hamme 1993; Claret, Diaz-Cordoves, & Gimenez 1995; Diaz-Cordoves, Claret, & Gimenez) for K giants fitted to the same two-parameter (square-root) law (Fig. 3).

     This first microlensing measurement of limb darkening was encouraging, but constructing realistic error bars for the results proved awkward. In traditional parameterizations for limb-darkening the coefficients c_λ and d_λ defined by

$$I_\lambda(\theta) = I_\lambda(0) \left[1 - c_\lambda(1 - \cos\theta) - d_\lambda(1 - \cos^n\theta)\right] \qquad \text{where } n = 0, 1/2, 2 \quad (1)$$

are correlated not only with each another, but also with other parameters in the microlensing fit because they carry information about the total flux F of

Figure 4. **Left:** The binary lens event MACHO 98-SMC-01 was exceptionally well-sampled due to the efforts of five microlensing teams. **Right:** Data over the second fold caustic crossing allowed one-parameter profiles to be deduced at several wavelengths for this A-dwarf source star in the SMC. (Based on Afonso et al. 2000).

the source. (Here θ is the angle between the normal to the stellar surface and the line of sight.) A different parameterization was therefore constructed for the analysis of fold caustic crossings (Albrow et al. 1999b),

$$I_\lambda(\theta) = \langle I_\lambda \rangle \left[1 - \Gamma_\lambda(1 - \frac{3}{2} \cos\theta) \right] \qquad \text{where} \ \langle I_\lambda \rangle \equiv \frac{F}{\pi\theta_*^2} \quad , \qquad (2)$$

which decouples the limb-darkening parameter Γ_λ from the source flux. To first order, $c_\lambda = 3\Gamma_\lambda/(\Gamma_\lambda + 2)$. This form was implemented in the analysis of the multiband data collected by five teams (Fig. 4) for the fold caustic crossing event MACHO 98-SMC-1 (Afonso et al. 2000). The source star was typed from spectra to be an A-dwarf in the Small Magellanic Cloud (and thus a radius $\theta_* = 80$ nanoarcsec!). As expected, limb darkening decreases with increasing wavelength and at given wavelength is smaller for a hot dwarf than a cool giant (Figs. 3 & 4). Unfortunately, no models of metal-poor A-dwarf stars were available for direct comparison with the 98-SMC-1 limb-darkening measurements.

A third microlensing limb-darkening measurement was made for the cool (4750 K) giant source star in the Galactic bulge event MACHO 97-BLG-41. This was a cusp-crossing event in which rotation of a binary lens was measured for the first time (Albrow et al. 2000, see also Menzies et al. 2000). The linear parameter $\Gamma_I = 0.42 \pm 0.09$, corresponding to $c_I = 0.52 \pm 0.10$, determined from the light curve agreed well with that of $c_I \approx 0.56$ from atmospheric models (Claret et al. 1995) of stars of the appropriate temperature and gravity.

The photometric precision required to recover linear limb-darkening coefficients with 10% accuracy has been estimated recently by Rhie & Bennett (2000), and found to be about 1% (relative photometry). As inspection of the residuals in Fig. 2 clearly reveals, a worldwide network of 1m-class telescopes is quite capable of this precision. At the current rate of observed caustic crossing events, the community can thus expect that microlensing will provide 2 or 3 limb-darkening measurements per year; indeed more results are now in preparation.

Figure 5.   **Left:** The azimuthally-averaged magnification as a function of fractional position r/ρ on stellar disk as a source (with $\rho = 1$) moves (from top to bottom) out of a caustic over a fold singularity. **Right:** Fractional error in the recovered intensity profile ($\delta I/I$) as a function of r/ρ for a direct point transit (top) and a fold crossing (bottom). Typical results are displayed for a 2m telescope, including limb-darkening effects for VIK passbands (Gaudi & Gould 1999).

3.2.   Spectroscopy

The magnification boost provided by microlensing can yield higher S/N spectra of faint sources than would otherwise be possible. Lennon et al. (1996) used microlensing to measure the effective temperature, gravity and metallicity of a G-dwarf in the bulge; at the time of the caustic boost, the 3.5m NTT had the collecting power of a 17.5m aperture. In another case, lithium was detected in a bulge turn-off star using Keck and microlensing (Minitti et al. 1998).

Attempts have been made to perform time-resolved spectroscopy during caustic crossings in order to detect the varying spectral signatures expected (Loeb & Sasselov 1995; Valls-Gabaud 1998) as light from different positions across the stellar disk (and thus different optical and physical depths) is differentially magnified. The caustic alert provided by the MACHO team (Alcock et al. 2000) allowed Lennon and colleagues (1996, 1997) to take spectra over the peak of the fold crossing in MACHO 96-BLG-3, though these did not extend far enough down the decline to detect spectral differences. Temporal coverage was also insufficient to detect strong spectral changes during the point caustic transit in MACHO 95-BLG-30, although slight equivalent width variations in TiO (Alcock et al. 1997) and Hα (Sasselov 1998) lines may have been seen.

4.   Stellar Tomography: A New Era of Stellar Atmosphere Physics

The ability of current microlensing collaborations to predict (fold) caustic crossings $\sim$1-3 days in advance opens a new era for stellar atmosphere physics. Followup teams, separately or in collaboration with existing microlensing networks, could obtain spectrophotometric data on auxiliary telescopes in order to take advantage of the magnification and resolution afforded by microlens caustics.

Figure 6.   Unlensed (top) and microlensed spectra for three different model atmospheres of a cool giant. Microlensed spectra are for a point caustic at the center (middle) and limb (bottom) of the source. Vertical dotted lines mark TiO bands (Heyrovský, Sasselov & Loeb 2000).

Theoretical expectations of how microlensing may contribute to our understanding of stellar atmospheres over the next decade are encouraging. Gaudi & Gould (1999) have simulated a 2m-class telescope with a 1Å-resolution spectrograph continuously observing a typical $V = 17$ ($\rho = 0.02$) bulge source undergoing a fold caustic crossing of 7 hours duration. They find that the intensity profile can be recovered to a precision of 10-20% using a spatial resolution of 10% across the star for most wavelengths. Most of the spatial resolution generated by fold caustics comes from the period in which the trailing limb is exiting the caustic curve. Direct transits of point caustics could provide even more reliable intensity profiles (Fig. 5), but due to geometric factors are much more unlikely to occur. These results appear to agree with the estimates derived from different approaches (Hendry et al. 1998; Gray & Coleman 2000).

Loeb & Sasselov (1995) noted that the "light curves" of atmospheric emission lines that are most prominent in the cool outer layers of giants will experience sharp peaks when the limb (rather than the center) of the source crosses a caustic. Recently, this work has been extended (Heyrovský, Sasselov & Loeb 2000) to lines across the whole optical spectrum to show how time-resolved spectroscopy during a caustic crossing can discriminate between different atmospheric models. For a given impact parameter, a particular line may appear in emission or absorption depending on the temperature structure of the star (Fig. 6). Since the duration of the caustic crossing is limited, 4m and 8m telescopes will be required to obtain the highest spectral resolution.

Experience and modeling thus indicates that any aperture can perform microlensing tomography of stellar atmospheres in the next decade, *provided that the community is willing to reschedule telescope access on a few days notice.*

Acknowledgements

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