Microlensing extended stellar sources

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Abstract. We have developed a code to compute multi-colour microlensing lightcurves for extended sources, including the effects of limb darkening and photospheric star spots as a function of spot temperature, position, size and lens trajectory. Our model also includes the effect of structure within the spot and rotation of the stellar source.

Our results indicate that star spots generally give a clear signature only for transit events. Moreover, this signature is strongly suppressed by limb darkening for spots close to the limb – although such spots can be detected by favourable lens trajectories.

1. Introduction

The amplification for a point source microlensing event is dependent only on the projected separation between lens and source. However, if the source size is comparable to the Einstein radius and the projected separation is small, it is necessary to treat the source as finite, with the amplification being calculated as an integral over the source star. Thus, the microlensing lightcurve also contains information about the source surface brightness profile.

Finite source effects were considered by Gould (1994) for the case in which a lens transits the star, allowing measurement of the lens proper motion and thus distinguishing between MC and Galactic MACHOs. Witt and Mao (1994) showed that the magnification profile of an extended source with a constant surface brightness profile was significantly different from the point source treatment for a 100 $R_\odot$ source microlensed by a 0.1 $M_\odot$ MACHO. The ability to recover the lens mass, transverse velocity and the source size are considerable assets in extended source microlensing, however rare the events may be.

The opportunity to use such events to provide information about the source star has also been investigated. Simmons et al. (1995) modelled the polarisation signature of an extended source microlensing event, assuming a pure electron scattering grey model atmosphere. They showed that including polarisation information significantly improves the accuracy of estimates of the source radius, as well as better constraining the radial surface brightness profile of the source. Gould (1997) suggested the use of extended source events to determine the rotation speed of red giants. The use of extended sources to estimate source limb darkening parameters has also been discussed by several authors (cf. Hendry et al. 1998; Valls-Gabaud 1998). Such an event produces a chromatic signature as the lens effectively sees a star of different radius in different photometric colour.
bands. This provides an unambiguous signature of microlensing, as opposed to that from a variable star (Valls-Gabaud 1998).

2. Microlensing spots

Recent literature has turned attention to the microlensing of extended sources with non-radially symmetric surface brightness profiles (cf. Hendry et al. 2000; Heyrovský and Sasselov 2000 (hereafter HS00); Kim et al. 2000). Microlensing provides an almost unique probe of such features: doppler imaging is inapplicable to late type stars, due principally to their long rotation periods, and direct optical imaging of stellar photospheres remains beyond the scope of current technology for all but a handful of stars. There is, nonetheless, already direct evidence for the presence of a large ‘hot spot’ on α Orionis, which shows strong limb darkening (Uitenbroek et al. 1998). Hot spots due to convection cells are likely to be present on the photospheres of red supergiants, and may be associated with non-radial oscillations. Gravitational imaging of such features on late type giants and supergiants would provide valuable constraints on stellar atmosphere models, placing limits on e.g. the form of the limb darkening law and the role of rotation.

While one can, of course, also consider the decremental effect of a cool spot, it seems pragmatic – in terms of spot detectability – to consider the impact of a hot spot on a cool, massive star. HS00 have demonstrated that hot central spots with a radius of 0.2$R_\star$ can produce a change in the microlensed flux $\geq 2\%$. We have improved their model in several important respects.

- We have incorporated the geometric foreshortening of circular spots on the photosphere close to the stellar limb, instead of placing circular disks on the star. Circular spots close to the limb appear increasingly elliptical.

- We have computed spot detectability both in terms of the percentage deviation from the unspotted flux and the goodness of fit of realistic, sparsely sampled observations – with magnitudes and errors appropriate to current MC and Bulge data – to the model of an unspotted star.

- We have considered linear, logarithmic and and square root limb darkening laws, with band-dependent LD coefficients from LTE stellar atmosphere models (Claret and Gimenez 1990) for U to K bands.

- Finally, we have considered the observational signatures of multiple spots, spots with temperature structure and spots on rotating stars – features which make our model somewhat more realistic.

3. Results

We have investigated the microlensing signatures of a range of spot parameters: radius $5^\circ$, $10^\circ$, $20^\circ$; spot temperature relative to stellar effective temperature ranging from $+200$ K $\rightarrow +1000$ K and $-200$ K $\rightarrow -1000$ K; spot geometry – i.e. varying the spot position on photosphere.
Figure 1. The microlensing light curve produced by 5 hot (+800K) circular spots on a 4000K log\( g = 2 \) star with stellar radius equal to the angular Einstein radius (AER) of the lens, being lensed at zero impact parameter. Note that the spots close to the limb appear foreshortened and do not contribute significantly to the microlensed flux. The unbroken, dashed, dot-dashed and dotted lines represent B, V, R and I bands respectively.

We summarise first our qualitative conclusions. As in HS00 our results show that central hot spots are detectable. Furthermore spots close to the limb can also be detected if the lens passes close to the feature, especially at minimum impact parameter (see Figs. 3 and 4 below). As the impact parameter increases, the central area where spots are detectable contracts, and only very large spots will produce detectable signals if the lens does not transit the source. A spot close to the limb produces only a small signal, as it is suppressed by the geometric foreshortening and the effects of the limb darkening. The stellar radius also affects the detectability of spots; however even on a small star (\( R_* \sim 10^{-5} \) AER) a plausible hot spot can be resolved at small impact parameter. The effect of a spot is clearly localised and of short duration, however. For example, a central 10° spot will produce a significant deviation for about 15% of the Einstein radius crossing time, with no effect in the lightcurve wings. Thus, excellent temporal sampling (\( \sim \) hours) is required to detect spots – even for surveys with high photometric precision.

3.1. Spot temperature and structure

The percentage deviation from the unspotted flux increases with the temperature of the spot (see Fig. 2) although the dependence on temperature is less strong than on spot position. Cool spots produce depressions in the lightcurve, but are less detectable than a hot spot with the same position, radius and (absolute) temperature difference. Not only is the light curve deviation smaller for a cool spot but it is also present over a shorter timescale. Including the effect of umbrae within spots produces additional small-scale structure in the light curve, but differing from the signature of a uniform temperature spot only over very short timescales.
3.2. Spot ‘imaging’

Since the microlensing lightcurve is essentially a convolution integral over the extended source, it is not surprising to find that the signatures of spots are non-unique, in the sense that spots of different shape and temperature structure can give rise to light curves which are identical within observational error. Thus, the use of microlensing as a tool for resolving detailed maps of the stellar photosphere is highly limited. Nevertheless, since the effect of each spot is fairly localised, one can at least use the light curve to place constraints on spot position and ‘filling factor’. Similarly, a failure to detect spot signatures from high time resolution observations of a transit event – particularly from e.g. a fold caustic crossing – can provide useful limits on surface activity for stellar atmosphere models.

3.3. Estimating stellar radii

The presence of starspots can also affect the estimation of the source parameters; specifically, neglecting the effects of maculae in the lightcurve can produce a biased determination of the stellar radius, and thus the lens Einstein radius and proper motion. For example, a star with a central hot spot will give a best fit to an unspotted star of smaller stellar radius; moreover, the impact of sparse sampling may ‘mask’ the presence of the spot feature and thus yield a perfectly acceptable $\chi^2$ to the smaller radius. The best fitting stellar radius estimated from V band data is typically 10% smaller than the true radius, for a range of plausible spot parameters. However, at longer wavelengths (e.g. I and K bands) the bias in the estimated radius is less severe, consistent with the reduced temperature sensitivity of the Planck function at these wavelengths. Moreover, cool spots do not produce a strong bias in the estimated radius.
3.4. Stellar rotation

The area and temperature contrast of a spot essentially determine the shape (i.e. amplitude and width) of the spot profile on the microlensing lightcurve. Interestingly, for the case of a rotating source, one can change the ratio of amplitude to width for the spot signature, since this effectively changes the transverse velocity of the lens with respect to the spot, without changing the lens transverse velocity with respect to the star as a whole. Whether the spot feature is narrowed or broadened depends on the orientation of the lens trajectory with respect to the rotation axis of the source. Even for the long rotation periods expected for late-type giants, the effect of rotation can have an impact on the observed lightcurve – e.g. for a source rotation period $\tau_S = 0.05 \, t_e$ and a spot of radius of 15°, the rotation of the source may bias the estimation of the spot radius by up to 10%. Of course a further complicating factor could be significant evolution in the surface distribution of spots during the lensing event – a problem more likely to be relevant for faster rotators.

3.5. Maps of spot detectability

As discussed above, the position of a spot on the stellar photosphere is the crucial factor which determines its detectability. As an illustration, Figures 3 and 4 show grey scale plots indicating the detectability of a 10° spot, of temperature 5000K, at various positions on the photosphere of a star with $T_{eff} = 4000$K, $\log g = 2$. Regions where the spot provides a larger signature are darker; in this example the darkest level on the plots indicates an average deviation of ≥10% compared with the unspotted lightcurve, while the lightest level indicates no significant deviation. Note that in the outer annulus of the stellar disk the spot is barely detectable, due to the effects of limb darkening and geometrical foreshortening, although this effect is more pronounced at high stellar latitudes, far from the lens trajectory. Note also that spots are more detectable in the V...
band – consistent with the greater bias in the determination of the stellar radius at shorter wavelengths.

4. Small scale radial oscillations

We have developed a model of the microlensing of stars displaying radial oscillations. Although intrinsic variability is adopted as an exclusion criterion by current microlensing surveys, this does not of course preclude the possibility that variable stars may themselves be microlensed (c.f. EROS-2, Ansari et al. 1995) – and such an observation could provide important information on issues such as stellar pulsation and asteroseismology. Complex lightcurves are produced by the radial oscillations of even a simplified model – see Fig. 5. Here we modelled a sinusoidal oscillation only in the stellar radius, neglecting chromatic variations other than those due to limb darkening. The period of oscillation was 5 days, which would typically correspond to about 4 complete cycles over the timescale of an event with small Einstein radius. Higher order non-radial oscillations can be modelled as a series of spots; however, detecting such features would be limited by the same criteria as discussed above – with the additional possible limitation of evolution during the event. Note that, due to the effect of limb darkening, for a fixed stellar radius the oscillation is more detectable at shorter wavelengths. Unlike spots, a small level of oscillation can be detected without the need for a transit or near-transit event. For example, if the impact parameter $\leq 0.2$ AER, a 2% change in the radius of a 0.001 AER radius star produces a highly significant deviation from the lightcurve modelled for a static star in the Bulge, for more than 25% of the event duration. For a well-sampled light curve, however, the deviations do not significantly bias the estimation of e.g. the stellar radius, although a poor or aliased sampling rate could introduce such a bias. Thus, detection of small scale oscillations will only occur if aggressive temporal sampling strategies are employed.
5. Spectroscopic signatures

Spectroscopic studies of transit microlensing events can provide strong constraints on stellar atmosphere models, (c.f. Heyrovský, Sasselov & Loeb 2000). We expect to see equivalent widths of spectral lines vary as the lens gravitationally images the source. Strong resonant lines such as Ly$\alpha$, CaII and MgII appear brighter at the limb. Thus, in transit microlensing events spectroscopic targeting of such lines would yield good estimates of the stellar radius and hence the Einstein radius – in a manner analogous to the polarimetric signature modelled by Simmons et al. (1995). Like the chromatic signature of extended source microlensing, the variation of line profile shape produces a unique discriminant between microlensing and intrinsic variability. To image spots, we need to probe lines sensitive to temperature structure: for example H$\alpha$ will be sensitive to active regions and molecular lines in the atmospheres of late-type giants will be sensitive to the presence of hot spots. However the atmospheres of red giants are poorly constrained by models: their limb darkening laws are extrapolated from limited data and are complicated by the presence of many molecules and by variations in metallicity. Moreover, many late-type giants possess extended circumstellar envelopes, for which microlensing would also present a powerful diagnostic tool. For example, the spectroscopic signature of a thin spherical shell of microlensed circumstellar material can provide an important probe of the density and velocity structure of the envelope (c.f. Ignace and Hendry 1999).

6. Conclusions

With the advent of automated ‘alert’ status for candidate events, the prospects for using microlensing as a tool for gravitational imaging and investigating stellar atmospheres are dramatically improved. Of crucial importance in such studies
are coordinated global observations to achieve the high level of sampling required to constrain models effectively. Observations of this quality are also precisely what is required to extract useful information from the microlensing of extended sources – making detailed modelling of such events a timely issue. Moreover, the intensive observation of second caustic crossings in binary events – currently being pursued with the principal goal of detecting planetary companions – would also provide powerful constraints on the range of spot-related phenomena discussed in this paper. We are currently, therefore, extending our analyses to consider the photometric, polarimetric and spectroscopic signatures of star spots lensed during line caustic crossing events.

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