SEEING STAR FORMATION REGIONS WITH GRAVITATIONAL MICROLENSING

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1. INTRODUCTION

Gravitational microlensing is now a well-established technique for the investigation of the distribution of compact (dark) matter in the universe. Furthermore, it also provides a powerful tool to study unresolved sources, such as in the case of the structure of QSOs, through temporal differential magnification (e.g., Yonehara et al. 1998).

From an observer’s point of view, gravitational microlensing can be naturally divided in two different regimes. In the case of Galactic microlensing, the optical depth is low and a single star microlenses another star within the Galactic halo or in one of the galaxies in the Local Group (Paczynski 1986b). With extragalactic microlensing, where the light from a distant quasar shines through a closer galaxy, the optical depth is roughly unity and many stars contribute to the overall microlensing effect (Paczynski 1986a). This paper considers this latter regime, where the source region is populated by a number of hot, young stars in a star-forming region. Such a situation will occur in strongly lensed, multiply imaged systems, such as the multiple images seen in galaxy clusters (Mellier 1999), or the case where an isolated galaxy gravitationally lenses a more distant galaxy (i.e., Warren et al. 1996).

In a similar vein, Lewis & Ibata (2001) investigated the effect of a cosmological distribution of compact objects on the surface brightness distributions of galaxies at $z < 0.5$, considering a small microlensing optical depth ($\leq 0.04$), and they determined that low-level fluctuations in surface brightness of $\sim 2\%$ should result. Lewis et al. (2000) extended that analysis to distant galaxies observed through galaxy clusters, assuming that dark matter is composed of compact objects. They focused on Abell 370 as a case study, concluding that for low luminosity ($\sim 10^4 L_\odot$), stellar populations would show rapid fluctuations, exceeding 10% of the mean in the highest cases.

In this contribution we address the question of what microlensing signatures should be apparent in the case of part of a galaxy that is lensed by another galaxy. In particular, we examine the case in which the lensed parts of the source galaxy are regions of star formation that are highly dominated by young, massive stars. Such a situation was recent presented by Smith et al. (2005), who reported the discovery of a new strong gravitationally lensed system, with an elliptical galaxy acting as the lens. The lens galaxy in this system is at redshift $z = 0.0345$, and the source, which is proposed to be a star formation region, is at $z \sim 0.45$, with the arcs formed by the gravitational mirage showing “knots” of an extreme blue color of $B-I_C = 1.1$ (extinction corrected). This discovery poses the idea that microlensing in the multiple images of these systems might be enable us to distinguish the type of source stars involved in the mirage and help in the interpretation of its nature.

Within the context of gravitational lensing, a star formation region would appear as a nonuniform source composed of a number of bright points in a more extended background. Hence, the microlensing imprint of such a source should show quite a different variability imprint from the uniform sources typically considered in gravitational microlensing experiments. The nature of this imprint is the basis of this current contribution.

2. MICROLENSING SIMULATIONS

For the purpose of this study we performed microlensing simulations by means of ray-shooting techniques (Paczynski 1986a; Schneider & Weiss 1987; Kayser et al. 1986; Wambsganss 1990; Witt 1993; Lewis et al. 1993). To compute magnification patterns, one has to select certain values for the convergence ($\kappa$), which represents the gravitational potential due to matter in the beam, and the shear ($\gamma$), which is the perturbation to the beam due to the large-scale distribution of matter. Typically, these parameters are drawn from a lens model for a particular system. For this study, however, representative values of $\kappa = 0.55$ and $\gamma = 0.55$ are employed, following Schechter et al. (2004), although other combinations would illustrate the situation equally; $\kappa$ here includes also any form of compact dark matter, where the effects of a smooth dark matter component are described in Schechter & Wambsganss (2002). Since high-resolution maps are required, we used a receiving field of two Einstein radii (ER),1 covered by a 2048$^2$ pixel area. The microlenses were randomly distributed and were selected to have the same mass, $M_{\mu, \text{lens}} = 1 M_\odot$. Again, the selection of the mass range is arbitrary for our purposes. However, it is important to note that, rather than covering a large area in the simulations, the key point remains in the resolution of the magnification patterns, because we are interested in small flux changes from pixel to pixel. Thus,

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1 The Einstein radius is defined in the source plane as $ER = (4GM/c^2)/(D_s/D_l)$, where $M$ is the mass of the microlens, $D$ is the angular distance to the source ($D_s$), the lens ($D_l$), and between the lens and the source ($D_\odot$), $c$ is the velocity of light, and $G$ is the gravitational constant.
we also selected a high number of rays, which resulted in over 700 pixel$^{-1}$ on average.

The next step in the simulations is introducing the effect of the source. To do this, we assumed a source plane at $z = 0.5$ and two different sizes of 0.1 and 0.5 ER, which correspond to a physical size of 0.02 and 0.1 pc, respectively, at that distance for the standard ΛCDM cosmology. Although star formation regions might be larger than the bigger size that we consider, these two examples illustrate the different effects due to their sizes and could be seen as clumps of star formation within larger regions (compact and ultracompact H ii regions as indicators of star formation might be <0.1 pc; see, e.g., Giveon et al. 2005 and references therein). We also assumed that our lens plane is at $z = 0.04$ (following the case of Smith et al. 2005). Depending on the stellar density of the source region, the number of stars in that region can vary from just a few up to hundreds. Considering first the 0.1 ER region, we “built” three different sources: one containing 8 stars, another containing 80, and the last one as a “uniform” source; that is, containing one star per pixel in the region (the number of stars are not representative of any particular region and have been chosen arbitrarily).

The results for the first region size are displayed in Figure 1. The top left panel corresponds to a $\sim$1 ER$^2$ region of the original magnification pattern. The top right panel shows the magnification pattern convolved with a region of 0.1 ER containing eight stars. The bottom right panel is the same as the previous one, but containing 80 stars. The bottom left panel shows the magnification panel convolved with a uniform source of the same physical size.

In all the panels the same track has been drawn, in order to compare the synthetic light curves to each other; these are depicted in Figure 2. The light curves are $\sim$1 ER long, showing the different expected fluctuations corresponding to the different scenarios. The magnification distributions for the magnification patterns corresponding to the different panels in Figure 1 are shown in Figure 3. Clearly the number of stars in the region has a significant influence on the resulting light curve; in effect, the presence of each star produces a “shift-and-add” to the magnification map, greatly increasing the number and overall density of caustics. This is reflected as additional peaks in the light curve. As the number of stars is increased to 80, some of the caustic structure has begun to wash out, leaving small-scale fluctuations superimposed on a more gentle background, whereas the smooth source (which can be thought of as a very high density of stars) has washed out all small-scale detail.

In Figure 4, for comparison, we consider a region size of 0.5 ER, containing also 8 stars, 80 stars, and a uniform source in the same manner as in Figure 1. Although their positions are the
Fig. 2.—Synthetic light curves for the corresponding panels in Fig. 1. When a few stars dominate the source region (top right), the variability can be easily distinguished from a uniform source (bottom left).

Fig. 3.—Relative probability distributions for the corresponding panels in Fig. 1.
same, the corresponding tracks shows completely different light curves compared to Figure 2, due to the new caustic structure of the magnification maps according to the different size of the region considered.

We interpret these figures as follows: If the magnification pattern is convolved with a uniform source profile (Fig. 1, bottom left), the result is always a smoother pattern, with smooth transitions in the value of the magnification from pixel to pixel; if the source area consists of a number of pointlike objects, the convolution will show many caustics slightly shifted with respect to one another, with no smooth transition between them. This translates into a rapid variability in the light curves of the corresponding source. Also, the size of the regions considered plays an active role in the final imprint of microlensing in the observational light curves.

3. APPLICATIONS AND DISCUSSION

The application of the simulations described in § 2 can be done in the following manner. If multiple lensed “knots” are detected in an image (see, e.g., Fig. 3c in Smith et al. 2005) and are thought to be star-forming regions, the flux will be highly dominated by young O stars. In principle, since young massive stars are rare due to their evolutionary process, only a few are expected to be in these star-forming knots (an ultraviolet and optical spectral atlas of the Small Magellanic Cloud includes <20 O stars; see Walborn et al. 2000). Observing these areas, for example, in the UV band, which characterizes regions of star formation, with periodic photometry, the variability of the observed light curves will be related to the number and the separation of these stars present in the star-forming regions (the contamination by late-type stars in the UV will be almost null). In practice, one could treat the problem statistically by simulating the observed variability and thus put limits on the amount and luminosity of young dominating stars. Knowing the luminosity of these stars accurately is important, because their masses derived by stellar evolutionary models and by stellar atmosphere models can be compared. Stellar evolution theory and initial mass function might take advantage of these results as well. Gravitational microlensing might be the only tool to “resolve” these stars in clusters of star formation, which are otherwise impossible to investigate in galaxies at moderate/high redshift.

Spectroscopy of microlensed star-forming regions might help to put limits on their nature as well. Gravitational microlensing of broad spectral lines in QSOs has been studied theoretically by a number of authors (e.g., Abajas et al. 2002; Lewis & Ibata 2004; Richards et al. 2004) and has been used to put limits on the size of the broad-line emitting regions of the QSOs. In those cases, the natural shape of a line is distorted by the complex net of caustics produced by the microlenses on the source plane. Since microlensing of the broad-line region is expected when its physical size is on the order of the Einstein radius of the lens projected onto the source plane, microlensed spectral lines give an idea of such physical sizes. In the same way, when observing typical spectral lines of O stars (e.g., O iv λ1371 and C iii λ1176 in the UV and He ii λ4686 and N iii λλ4634, 4640 in the optical), one would expect the lines to be deformed by the presence of the caustics (due to magnifications/demagnifications), and these variations in the spectral lines might reveal the size and populations of the star-forming regions.

To illustrate this, we plot in Figure 5 the spectra of an O star (top) and a solar-like G star (bottom), obtained from the Kurucz
models database.\textsuperscript{2} For any unresolved star formation region, the (far-)UV range of the spectrum will be dominated by these O stars. Fluxes in UV for late-type stars are several orders of magnitude lower, and thus they do not contribute significantly to the total luminosity; therefore, the flux distribution in the top panel of Figure 5 might be a representative one for that part of the spectrum (different lines might be present, obviously). Microlensing affecting this part of the spectrum will only show an enhancement of the flux. However, the effect is slightly different when using the optical range of the spectrum. In this case, the flux contribution due to late-type stars starts to be dominant, although flux from O stars is still significantly present. We construct a toy star formation region model, merging the spectra of the O star and the G star shown in Figure 5, assuming that 90% of the total flux comes from solar-like stars and the rest is produced by early-type stars. The toy model is depicted in Figure 6 (\textit{lower line}; spectrum marked as “O-star + G-star”), showing only the 1500–5500 Å wavelength interval. When the star formation region travels across the magnification pattern in Figure 1, late-type stars will act as a constant flux background as a whole, and microlensing will affect mainly O stars. In this way, the microlensing signature in the spectra will be a flux ratio variation between O stars and spectral lines from late-type stars. This is shown also in Figure 6 (\textit{upper line}; spectrum marked as “O-star + G-star + microlensing”). There is not only an enhancement of the flux in the bluest part of the spectrum, but also a deformation of certain lines due to the different microlensing effects on the different types of stars. In Figures 7 and 8 we repeat the procedure, but with a different relative flux between the two types of stars. In Figure 7, 1% of the flux comes from O-type stars and 99% comes from late-type stars; in Figure 8, the percentages are 0.1% and 99.9% for early- and late-type stars, respectively. As shown in Figure 2, high variability is expected. Both Figures 2 and 3 show that the amount of variability depends on the nature of the star formation regions (number of stars, size of the regions, etc.). This means that by

\textsuperscript{2} Available at http://stsdas.stsci.edu/ETC/STIS/stis..., models.html.

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig5.png}
\caption{Spectra of O star and G star models. The contribution of a solar-type star to the total flux in the (far-)UV band can be ignored, since it is several orders of magnitudes lower. See text for references.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig6.png}
\caption{Toy model for a star formation region, made of two superimposed spectra of an O star and a G star. The relative flux between the two types of stars is 10% and 90% for the O stars and G stars, respectively. We introduce the microlensing effect as an enhancement in the flux of the O stars by a factor of 1.6, which corresponds to a decrease of 0.5 mag (\textit{upper line}).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig7.png}
\caption{Same as Fig. 6, but for a flux contribution of 1% and 99% from the O star and the G star, respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig8.png}
\caption{Same as Fig. 6, but for a flux contribution of 0.1% and 99.9% from the O star and the G star, respectively.}
\end{figure}
comparing several consecutive spectra, one would be able to statistically determine the relative flux variability of the spectral lines and continuum due to the presence of the caustics and thus compare them with the expected one from the simulations, putting limits to the number and distribution of the early-type stars.

A key point to note regarding the detection of these microlensing effects on star formation regions is the timescale of the events. If we use the lens configuration described in § 2, we can estimate a typical separation between microcaustics in the magnification maps in Figure 2. This separation is \( \sim 0.005 \) ER in the top right panel, which corresponds to approximately \( 10^{-3} \) pc. If we assume a transverse velocity for the source galaxy of \( \sim 6000 \) km s\(^{-1}\) (see Kayser et al. 1986), the resulting timescale for the events is \( \sim 50 \) days. The timescales of the events get shorter when the number of O stars gets higher, although the flux variability is smaller. This means that six data points in a time period of around 3 months should be able to describe the type of variability involved in the gravitational microlensing scenario.

4. CONCLUSIONS

We described in this contribution how to apply gravitational microlensing to the observations of unresolved extragalactic star-forming regions. The discussion shows that, due to the configuration of the caustics in the magnification maps of the region, rapid monitoring campaigns, both photometric and spectroscopic, would be able to reveal high variability fluctuations due to the number of early-type stars. The specific amount of variability will depend on the number of stars and their distribution in the region, as well as on the exact configuration of the microlenses in the lensing galaxy. Thus, the study of a particular system requires the knowledge of a lens model to perform the right simulations, and the analysis of the results should be based on a statistical approach. The advantage of the method, if these circumstances take effect, is that we might be able to investigate star formation regions that are difficult to analyze with more traditional techniques.

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