Astro. Lett. and Communications 1987, Vol. 25, pp. 255–261
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Is Gravitational Lensing a Local Phenomenon Caused by Pop III Objects?

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(Received January 31, 1986)

1. ROLE OF LOCAL DEFLECTORS IN GRAVITATIONAL LENSING

A number of candidates for multiply imaged quasars have been reported over the past few years (Walsh, Carswell and Weymann, 1979; Weymann *et al.*, 1980; Weedman *et al.*, 1982; Lawrence *et al.*, 1984; Djorgovski and Spinrad, 1984; Huchra *et al.*, 1985, Tyson, 1985). The first gravitational lens system 0957 + 561 A, B made up of two nearly identical quasars, separated by 6.15 arc sec, was extensively studied by including the combined gravitational influence of a giant elliptical galaxy and a cluster (Young *et al.*, 1980; Narasimha, Subramanian and Chitre, 1984). The rest of the multiple image configurations have also been suitably modelled (Chitre, 1985). The gravitational deflectors in these models are galaxies and/or clusters located between the observer and the sources at extragalactic distances. The lenses for all the foregoing systems have been taken to be extended, transparent objects.

It has been shown by Burke (1981) using general topological considerations that an extended distribution of matter in the form of a galaxy or a cluster always produces an odd number of image. Remarkably, only an even number of gravitationally produced components have been detected in most of the lens systems discovered todate. This has imposed severe constraints on the lens models in order to dim the third (or fifth) image to a flux level below the detection limit. Furthermore, it has not been possible to identify unambiguously gravitational lenses for all the systems. In fact, in only three cases of multiple quasars there is a clear indication of the presence of a lens en route (e.g. 0957 + 561; 2016 + 112 and 2237 + 0305).

The foregoing considerations—fine tuning and freedom in the parameter space; absence of the third image; lack of an obvious lensing candidate in half the lens systems detected so far—have prompted us to examine an alternative scenario: at least in *some* of the reported cases, the lensing phenomena could be due to the compact black hole remnants of Pop III objects in the halo of our own galaxy. We should like to emphasize right at the outset that we are not claiming that *all* the lensing events are due to the interception by Pop III objects in our galaxy. It is merely a suggestion to enquire whether some of the observed features like separation and intensity ratio of the images could be attributed to a lensing action by the massive ($\gtrsim 10^6\,M_\odot$) black hole remnants of Pop III objects. The main purpose of this note is to point out that there exists a prima facie case, at any rate for some of the multiply imaged quasars, for the production of two components of a single source by gravitational deflection by Pop III objects. Recently, Paczynski (1985) has examined the problem of gravitational microlensing by massive objects in the halo of the galaxy, although in a somewhat different context.

We outline the necessary mathematics in the following section and compare theoretical results with the observations in Section 3.

2. THE BASIC MODEL

We assume that the halo of our galaxy contains compact black hole remnants of Pop III objects with typical masses $\gtrsim 10^6\,M_\odot$. Within a radius of about 200 kpc, the halo mass may be few times $10^{12}\,M_\odot$. If most of the halo mass is contributed by Pop III objects, then there will be about 10^5–10^6 objects in the halo (Carr, 1985).

Consider any one of these objects coming between a distant quasar and us. For the geometry described in Figure 1 (with $\alpha \neq 0$), two images will be produced at angles θ_1 and θ_2, which are the roots of the following equation (Liebes, 1964;

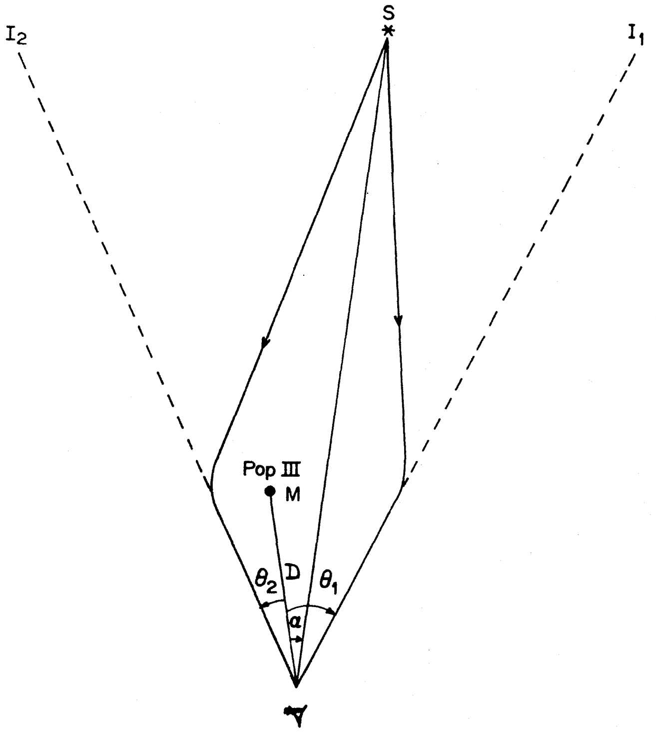

FIGURE 1 Source S is intercepted by Pop III object with mass M located at distance D from the observer giving rise to images I_1 and I_2 at angular distances θ_1 and θ_2 respectively from the sight-line to the deflector; α is the angle between the sight-lines to the source and the deflector.

Refsdal, 1964; Saslaw, Narasimha and Chitre, 1985):

$$\theta^2 - \alpha\theta - \theta_0^2 = 0, \tag{1}$$

where θ is the angle between the source and the image and,

$$\theta_0^2 \cong \frac{4GM}{c^2D} \tag{2}$$

Here M is the mass of the compact object and D is the distance to this object ($\sim 10^2$ kpc). In writing (2) we have assumed that the distance to the source ($\sim 10^3$ Mpc) is far larger than D ($\sim 10^2$ kpc). The intensity ratio of the two images is given by (cf. Liebes, 1964)

$$(I_1/I_2) \equiv k = (\eta + 1)^2/(\eta - 1)^2 \tag{3}$$

with,

$$\eta^2 = 1 + \frac{4\theta_0^2}{\alpha^2}, \tag{4}$$

while the angular separation between the images is,

$$\Delta\theta \equiv \theta_1 + \theta_2 = \alpha\left[1 + \frac{4\theta_0^2}{\alpha^2}\right]^{1/2} = \alpha\eta \tag{5}$$

Combining (3), (4) and using (2) we can obtain the relation,

$$\alpha^2 = \frac{4GM}{c^2D}\frac{(\sqrt{k} - 1)^2}{\sqrt{k}} \tag{6}$$

and using (5) we finally get

$$\Delta\theta = \left(\frac{4GM}{c^2D}\right)^{1/2}\frac{(\sqrt{k} + 1)}{k^{1/4}} \tag{7}$$

or in terms of typical values,

$$\Delta\theta = (0.84 \text{ arc sec})\left\{\frac{\sqrt{k} + 1}{k^{1/4}}\right\}\left(\frac{M}{3 \times 10^6\, \mathrm{M}_\odot}\right)^{1/2}\left(\frac{D}{30 \text{ kpc}}\right)^{-1/2} \tag{8}$$

This simple formula contains the essence of the lensing by Pop III objects. The only free parameters are: the location of the Pop III remnant (D, α) and its mass M. For convenience we have eliminated α in favour of k; *but this is only for the sake of mathematical convenience.* Our model, given (M, D and α) can *predict* correctly *both* the intensity ratio *and* angular separation [see discussion below and Table I]. The distance D can vary from 20 kpc to 200 kpc in our galaxy halo. The mass M can vary in the range of $(3–6) \times 10^6\, \mathrm{M}_\odot$. For all the observed quasars $(\sqrt{k} + 1)k^{-1/4}$ is of the order of 2. Thus, a margin of a factor of 4 in $(MD^{-1})^{1/2}$ would allow us to model any lens system with separations in the range 1 arc sec–8 arc sec, without any evident discomfort or fine tuning!

The above discussion is based on the assumption that a *single* remnant of Pop III dominates the bending of a light trajectory (rather than the average potential

TABLE I

Lens System	Angular Separation (observed) (arc sec)	Intensity Ratio (observed)	Mass of Lens (M) (in $10^6\,M_\odot$)	Distance to Lens (L) (kpc)
2237 + 030	1.2	1.1	2.5	50
2016 + 112	3.4	1.6	8	30
1635 + 267	3.8	4.0	10	20
0957 + 561	6.15	1.3	25	20
2345 + 007	7.13	4.0	30	20

Typical M and D values which reproduce the observed angular separation and intensity ratios are indicated. We have excluded the triple quasar 1115 + 080 from the list. The observed angular separation and the intensity ratio are approximately estimated average values.

of the smoothed-out halo), an assumption that *is* eminently valid for the Pop III objects which we are considering. Since there are $\sim(4\pi)^{-1}\,10^5$ objects per square radian, the mean interobject separation is about $\sim(4\pi \times 10^{-5})^{1/2} \sim 10^{-2}$ radians. This is much larger than the relevant angles in Eq. (8) which are $\sim 4 \times 10^{-6}$ radians. In other words, we are considering close encounters, between the light rays from distant quasars and any *one* of Pop III objects; the next nearest object is too far away to influence the beam. [We note, in passing, that the situation would be very different if dark matter is made of lighter constituents, like Jupiters or neutrinos. The number density will be much higher than 10^5 and hence the interobject separation will be comparable to the angles we are considering. Our analysis will then no longer be applicable.]

In general we expect Pop III objects to be distributed over a range of M and D values. Given some theoretical model for these distribution functions, Eqs. (2), (4) and (5) determine the distribution of θ_0, η, $\Delta\theta$ respectively. Quantitative estimates of the distribution of these values can only be made when the fundamental distribution of M, D are known.

3. COMPARISON WITH OBSERVATIONS

The theoretical model is compared with the observations in Table I. We have excluded the triple lens system (1115 + 080) from consideration because it clearly shows four images. All others can be modelled with M in the range of $(2.5 - 30) \times 10^6\,M_\odot$ and D in the range of (20 kpc–50 kpc). The three systems 2237 + 030, 2016 + 112 and 1635 + 267 are evidently explained in a very natural fashion. The systems 0957 + 561 and 2345 + 007 having large angular separations require the extreme ranges in parameters, but in any case 0957 + 561 has the added complication that there is a lens galaxy-cluster present en route to the quasar. This very first gravitational lens system detected should not perhaps be included in our consideration.

In order for the model to work, we need an alignment of the deflector and the source closer that an angular separation of the order of α. The probability to have at least one Pop III remnant within this angular distance can be easily computed;

using Eq. (6)

$$P \cong \left(\frac{M_{\text{halo}}}{M}\right)\frac{\alpha^2}{16} \cong 3.3 \times 10^{-6}\left\{\frac{M_{\text{halo}}}{10^{12}\,\text{M}_\odot}\right\}\left(\frac{D}{30\,\text{kpc}}\right)^{-1} \tag{9}$$

This probability is of the same order as that for lensing alignment in conventional modelling. We would like to interpret (9) as follows: Pop III objects are as likely to produce the same effect as distant lenses. Therefore, one may naively expect three out of six known cases to be accounted for by lensing action due to Pop III.

4. CRITICAL EVALUATION OF THE MODEL

On the whole, how does the new scenario compare with the conventional one? The nice features of this scenario are the following:

(i) This leads to the two image configuration by a point mass deflector in a natural fashion without any fine-tuning of the lens parameters.

(ii) It can explain the absence of lensing candidates in some of the cases. Note that a positive identification of a lensing candidate has been made only in 3 cases.

(iii) The model has very few parameters to adjust. Both the mass and distance in the present model are much more narrowly constrained than the range of parameters (core density, velocity dispersion, core radius and redshift for each intervening lensing object) which are used in the usual picture of lensing by extended deflectors. In general, this scenario would seem to us much simpler than the conventional one.

On the negative side, the idea suffers from the following short-comings:

(i) Clearly all the systems cannot be attributed to lensing by Pop III. There is at least one case with a clear 4-image configuration, and we certainly cannot ignore the presence of intercepting galaxy + cluster in the case of 0957 + 561. (Probably the former could be lensed by invoking two intervening Pop III objects.)

(ii) Nobody has "seen" a Pop III remnant. While the possibility that dark matter consists of Pop III remnants cannot be entirely ruled out, it only enjoys (at best!) a minority support.

As a tentative defence against the above two objections, we would like to point out the following facts: (i) All available evidence shows diversity in the nature of lensing objects. By including Pop III, we are merely adding to this list. (ii) The nature of dark matter is still somewhat of a mystery. Hot and cold dark matter scenarios are not without their own brand of difficulties (Blumenthal *et al.,* 1984). It is perhaps desirable to temper one's strong personal views on the nature of dark matter with a sensible regard for the status of observations.

It should be stressed that the gravitational lensing action which we have considered operates best when the Pop III objects are located within the halo of our own galaxy. Clearly, if our galaxy halo is supposed to have such objects, then it is highly likely that they will also be present in the haloes of other galaxies. But it can be readily seen from Eq. (8) that the angular separation between quasar images due to lensing by Pop III objects at cosmological distances ($\gtrsim 300$ Mpc) is of the order of 10 marcsec. In such a situation the light beam from a distant quasar will be split into images with a separation of ~arc sec by the lensing action of the large-scale deflector (galaxy/cluster of galaxies) and the Pop III objects resident in these deflectors will merely act as minilenses to split the image further into sub-images.

There is another effect which will manifest should the quasar be intercepted by a Pop III object. These lenses are liable to have a transverse motion, V_t of several hundred km/s. This proper motion will cause significant intensity variations of the quasar image over time-scales $\sim L\Delta\theta/V_t \simeq$ few *hundred* years (cf. Subramanian, Chitre and Narasimha, 1985). Note that the lensing effect which we have considered works best for situations where the brightness ratios between images, $k = I_1/I_2$, is significantly different from unity, which is in fact the case for most of the observed lens systems. Should $k \simeq 1$, then the impact angle α will be pretty small and the probability of such an alignment will turn out to be negligible. We may speculate with Turner (1968) that the lensing by dark objects of the type we have considered are likely to be operating in systems like 1635 + 267, 2345 + 007 and 0023 + 171 which have large intensity ratios between images and for which no lens candidates have as yet been identified.

The physical gravitational radius of influence of a Pop III object with mass M and placed at a distance D ($\ll$ observer – source distance) is given by

$$r_0 \equiv \left(\frac{4GDM}{c^2}\right)^{1/2} \approx 2 \times 10^{17}\,\mathrm{cm}\left(\frac{M}{10^6\,\mathrm{M}_\odot}\right)^{1/2}\left(\frac{D}{30\,\mathrm{kpc}}\right)^{1/2} \tag{10}$$

The VLBI core-jet structures in 0957 + 561 extend to ~50 maresec which, at the distance of the quasar, corresponds to $\gtrsim 3 \times 10^{20}$ cm. The radio structures thus stretch well beyond the circle of influence of a Pop III object located in the halo of our galaxy. However, such an object in the halo of a distant galaxy would almost certainly affect the radio structure of the quasar and will look different when it is lensed by Pop III object than when it is lensed by a large-scale deflector like a galaxy/cluster. Indeed, this feature can be used as a test of the existence of Pop III objects which would have a distinctly different lensing effect on the compact continuum regions compared to the larger radio emitting regions (Subramanian and Chitre, 1986).

As more gravitational lens candidates emerge, one can test the validity of (8) with M and D in the range suggested. If more and more cases occur which cannot be explained by this range of values for (M/D) then the contribution to lensing by Pop III objects may be ignored.

If in the future an increasing number of lens systems with an odd number of images are observed, once again Pop III objects may not play any significant role in the lensing phenomenon. The double image nature is a clean prediction of the present model.

The time delay for the variation of intensities in the two images will be different from the time delays predicted for the conventional models involving transparent lenses [the path difference will scale with the distance to the deflector D, which is smaller in our case; we expect time delays ~2 minutes in the present scenario]. A decisive test of this model would probably be the observation of time delays and a persistent absence of (a) large time delays and (b) lens candidates for a multiple quasar system. The model clearly "sticks its neck out", which may be considered another point in its favour, but the answer to the question raised in the title can only be left to the reader to figure out according to his own taste!

It is a pleasure to thank K. Subramanian, J. V. Narlikar and G. R. Burbidge for valuable comments.

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