Effect of gravitational lenses on the microwave background, and 1146+111B,C

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We suggest a simple check of the proposal by Turner *et al.*[1] that the pair of quasars 1146+111B,C are, in fact, two images of the same object lensed by an intervening object. If the lens is a cluster, either of normal galaxies or of dark matter, the microwave background seen through the cluster will be distorted by the Zeldovich–Sunyaev effect at the 10^{-3} level.

A new and exceptional candidate for an astronomical gravitational lens system has been found by Turner *et al.*[1]. Two quasars separated on the sky by 157 arc s have very similar spectra and redshifts agreeing to within 100 km s^{-1}. If confirmed by further observations, this would be by far the largest angular splitting observed. Galaxies in clusters will typically produce a splitting of ~3 arc s (ref. 2), not far from the average of the six known systems, which is 4 arc s. As the splitting angle is proportional to $(v_{\|}/c)^2$, where $v_{\|}$ is the internal one-component velocity dispersion and c is the velocity of light, clusters of galaxies can produce far larger splittings. In fact, on this basis Paczynski[3] proposed that the 1146+111B,C pair might be such a lens system before the recent observations.

This system, if it is a gravitational lens, may have been produced by a massive black hole[4] or by a cosmic string[5], but it is worth exploring the more conventional possibility that it arises from an intervening cluster of matter. We now show that, if a cluster has acted as a gravitational lens, it is essentially guaranteed that it will also produce an observable Zeldovich–Sunyaev effect. The new lens system corresponds to a very large and detectable effect. This is not surprising, as typical clusters can produce a nearly detectable effect, and this lens system would require an unusual cluster.

Turner *et al.*[2] showed that, under normal circumstances, the production of a double image requires a projected mass distribution (on the plane of the sky) greater than Σ_c, where for a universe with density parameter $\Omega_0=1$

$$\Sigma_c=\frac{cH_0}{8\pi G}\,\frac{x^2(y^{1/2}-1)}{(y^{1/2}-x^{1/2})(x^{1/2}-1)} \tag{1}$$

where $y\equiv 1+z_Q$ and $x\equiv 1+z_L$ are the redshifts of the quasar and the lens, respectively, $H_0=100h$ km s^{-1} Mpc^{-1} is the Hubble constant, and G is the universal gravitational constant. This surface density is of order 1 g cm^{-2}, and thus the optical depth to electron scattering (τ_{es}) is likely to be significant for all gravitational lens systems. If the ratio of baryonic mass to total mass is f_b, and the matter in the lens has normal composition, and is ionized, then

$$\tau_{es,c}=0.35f_b h\Sigma_c \tag{2}$$

so that, if $\Sigma>\Sigma_c$, then $\tau_{es}>\tau_{es,c}\simeq 1$.

The angular splitting ($\Delta\theta$) for an isothermal distribution of mass is, for the chosen cosmology[2],

$$\Delta\theta=(v_{\|}/c)^2 8\pi\frac{y^{1/2}-x^{1/2}}{x^{1/2}(y^{1/2}-1)} \tag{3}$$

For an isothermal sphere with gas in equilibrium with the same distribution as the gravitating mass, $v_{\|}^2=C_s^2$, where c_s is the speed of sound, we will take as a general result that

$$c_s^2\equiv\beta v_{\|}^2 \tag{4}$$

Finally, the Zeldovich–Sunyaev effect for temperature fluctuations in the microwave background can be written as

$$\Delta T/T=-2.2\times 10^3 c_s^2/c^2\tau_{es} \tag{5}$$

in the long-wavelength limit.

Combining equations (1)–(5) we obtain

$$|\Delta T/T|\geq|(\Delta T/T)c|=1.78f_b\beta\Delta\theta h g(x,y) \tag{6}$$

where

$$g(x,y)\equiv\frac{x^{5/2}(y^{1/2}-1)^2}{(y^{1/2}-x^{1/2})^2(x^{1/2}-1)}$$

For the case at hand, $y=2.01$. The minimal value of $g(x,y)$ occurs, for a fixed quasar position y, at $x=[y^{1/2}+3/4-((4y^{1/2}+3)^2-40y^{1/2})^{1/2}/4]^2$. In this case this is $x=1.20$, which gives a value of $g(x,y)=27.8$. Therefore, for the system 1146+111B,C where $\Delta\theta=157$ arc s, we find

$$|\Delta T/T|\geq 0.038\beta f_b h \tag{7}$$

From light-element nucleosynthesis, the fraction of the critical density contributed by baryons, $\Omega_b\simeq 0.03\ h^{-2}$ (ref. 6), so that if $f_b=\Omega_b$, then $|\Delta T/T|=1.2\times 10^{-3}\beta/h^{-2}$, which should definitely be detectable. For the more likely value of $x=1.5$, the numerical coefficient is larger by a factor of ~1.77.

This calculation has assumed that the cluster has the shape of an isothermal sphere. Is this a fair assumption? The relationship between the angular splitting and the surface density of material is relatively insensitive to the shape of the cluster. However, if the cluster is elongated towards the observer, then the integrated electron pressure is no longer simply related to the angular splitting. This is the significance of the factor β in our calculation. Assuming we are observing lensing due to a prolate spheroid pointed at us with an axis ratio <1, then β is roughly proportional to the value of the axis ratio. For an average lens system we can be confident that this will not greatly lower our estimate of the induced temperature distortion. For the particular case of 1146+111B,C we have no basis on which to constrain the axis ratio.

Suppose that the region has, for some reason, excluded gas, or that the gas has been kept cold, or that f_b is in fact quite small. In this case, there will be no electrons in the intracluster gas and therefore no Zeldovich–Sunyaev effect. There will still be an effect on the microwave background due to the mass concentration. This is due to purely gravitational effects on the background photons as they traverse the lens system. This effect is approximately given by $|\Delta T/T|=(\Delta\theta)^2$ (see ref. 7), which in this case gives a temperature distortion of $\sim 6\times 10^{-7}$. This is smaller than present limits on detectability.

We see that an unusual cluster of a normal type would produce a large effect. Even if the cluster were made of dark matter without galaxies, but contained baryons in a normal ratio, the effect would be undiminished. In the unlikely event that the cluster were devoid of hot gas or of some very unusual shape so that the normal effect were absent, there would still be an effect not far below our present ability to look for temperature distortions. These results suggest that the microwave background at the lens system 1146+111B,C, and any other lens candidates with large separations, necessarily provide us with an independent way of confirming their status as gravitational lenses.

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