MOVING GRAVITATIONAL LENSES

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Summary

A massive object distorts the path of light passing near it. If the object's metric changes at a different rate than that of the Universe, then a monochromatic source behind the object will change in frequency and flux relative to a similar source elsewhere. Contracting lenses and large masses in the early Universe provide effects of this type, but an alternative mechanism for producing such an effect is *motion* of the lensing object. A lensing object moving across the line of sight should cause (a) a redshift difference between multiple images of a background object (e.g. a quasar lensed by a galaxy) and (b) a brightness anisotropy in the microwave background radiation. Effect (a) is unlikely to be measurable for the multiple images formed by 'conventional' astrophysical objects, although a *string* may produce a detectable effect if it has sufficient mass per unit length. Effect (b) should soon be detectable for clusters of galaxies with large peculiar velocities.

Redshift effects from changing gravitational fields

Rees & Sciama (1968), Dyer (1976), Nottale (1984), and others have discussed the effect on background sources or the background radiation of a massive object surrounded by a void embedded in an expanding Universe. As light passes through the 'vacuole', it is retarded relative to light which does not pass through the structure, so that a view of an anomalously early phase of the Universe is seen. If the vacuole expands or contracts at a different rate from the external Universe, light passing through it is redshifted differently from light that misses it. As a consequence, the brightness and spectrum of sources (and the background radiation) behind the vacuole are changed relative to other sources. This is a particular example of a more general phenomenon, in which optical effects are produced by localised changes in the metric that are unlike the changes in the metric of the Universe as a whole. A somewhat different effect arises when an object of fixed properties moves relative to the Hubble flow.

In the frame of a lens moving at velocity $\mathbf{v}$, the frequency of a monochromatic light source depends on the direction of the source relative to the direction of motion of the lens. The effect of the lens is to cause a change δ in the direction of a light ray without a change in frequency. Back in the frame of the original source, a stationary observer would see that light emerging from the lens is no longer parallel to light entering the lens. The Lorentz transformations to and from the lens frame do not cancel out as they would have done had there been no deflection, and the observed frequency of the deflected light depends on δ and v, and the direction of the light source relative to $\mathbf{v}$. For non-relativistic lens velocities and small angles of deflection, it is clear that the frequency shift should be of order $\delta \times v/c$. The exact result, for small deflections but arbitrary lens velocity, is

$$\frac{\Delta\nu}{\nu} = \gamma\beta\delta \sin\alpha \, \cos\phi \tag{1}$$

where ν is the frequency of light emitted by the source, $\Delta\nu$ is the difference between the observed and emitted frequencies, $\beta = v/c$, $\gamma = (1 - \beta^2)^{-1/2}$, α is the angle between the lens velocity vector ($\mathbf{v}$) and the line of sight to the lens, and ϕ is the angle between $\mathbf{v}$ and the emerging light ray projected onto the sky (Birkinshaw & Gull 1983). Note from the dependence on α that this effect arises from the *transverse* motion of the lens across the line of sight: measurement of $\Delta\nu$ provides a test for transverse motions of distant lensing objects.

Multiple images of quasars near galaxies

Clearly the frequency shift (1) might be sought as a differential redshift between the multiple images of a quasar formed near an elliptical galaxy (Fig. 1). Consider the 0957+561 system as an example. In this case the separation of the A and B images is $\Delta\theta = 6.17$ arcsec (Gorenstein *et al.* 1984), so that the frequency shift between lines in the spectra of A and B is $\frac{\Delta\nu}{\nu} \approx \frac{v}{c}\,\Delta\theta$, or a shift

$$\Delta\lambda \approx 5 \times 10^{-5}\,(v/1000 \text{ km s}^{-1}) \quad \text{nm} \tag{2}$$

in the wavelengths of optical lines. Since the narrowest line feature in a quasar spectrum has width $> 10^4\Delta\lambda$, it is clear that this shift is too small to be detected, even without considering the intrinsic differences that are likely because of the time delay and different lines of sight of the images.

The smallness of $\Delta\lambda$ can be understood easily as a consequence of the low density and velocity of most conventional astrophysical objects: if R_S is the Schwarzschild radius corresponding to the mass of the lens, the frequency shift for a given image

$$\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c} \cdot \frac{R_S}{R} \tag{3}$$

where R is the distance of closest approach of the ray to the centre of the lens. Equation (3) makes it clear that $\Delta\lambda$ can become large only for rapidly-moving, compact objects.

Figure 1. A schematic diagram of the location of the three images (marked by numbered crosses) of a quasar formed by an elliptical galaxy (indicated by a representative isophote). The vector represents the direction of the peculiar velocity (v) of the galaxy projected in the plane of the sky.

Strings and multiple images of quasars

A much larger differential redshift should be seen in multiple images of quasars formed by cosmic strings. Suppose that the close pair of quasars 1146+111B and C represents an example of the lensing effect of a string (Turner *et al.* 1986; Gott 1986). B and C are of similar brightness (as is required), and are separated by about 2.6 arcmin. This corresponds to a string with mass per unit length $\mu \approx 4 \times 10^{22}$ kg m^{-1} between the quasars, and the wavelength shift between the images is

$$\Delta\lambda \approx 0.4\,\gamma\beta \quad \text{nm} \tag{4}$$

for optical lines. Essentially all strings are expected to move at relativistic speeds, with $\beta\gamma \approx 1$. If this is true for a string in the 1146+111B,C system, a differential redshift $\Delta z \approx 0.001$ should appear between the B and C images. A redshift difference of this size might also appear if the quasars are independent members of a single cluster. (Note that a second contribution to a redshift difference arises from the different time delays for the two images, but this is of order δ^2, and hence is smaller than the velocity-produced delay above; Gott 1985)

If the Universe holds strings with μ greater than the value suggested for 1146+111B,C, the redshifts of the two images of a lensed quasar might be distinctly different, and the lensing system might be difficult to recognise. The similarity in the quasar spectra and brightnesses may be further reduced by differences in the absorbing medium along the line of sight, changes in the quasar spectrum over the differential light travel time, etc., so that there may be significant problems in using optical search methods to locate strings.

Figure 2. A schematic diagram of the location of the two images (marked by numbered crosses) of a quasar formed by an string. Since the string is curved, it tends to move at relativistic speed (v), as indicated by the vector.

Background radiation anisotropy

Figure 3 illustrates the theoretical pattern of frequency shifts that is expected around a moving lens with a density distribution of the form

$$\rho(\mathbf{r}) = \begin{cases} \left(1 + r^2/r_c^2\right)^{-3/2} & r < r_0 \\ 0 & r > r_0 \end{cases}$$

with $r_0 = 4r_c$. As indicated earlier, the frequency shifts themselves will probably not be directly observable in the redshifts of multiply-imaged quasars, but the associated changes in the brightness of a background radiation may be observable: light from a uniform background is preferentially shifted to higher frequencies on one side of the lens, lower frequencies on the other, so that a brightness change is seen across the lens. When account is taken of the change in solid angle occupied by a bundle of rays (Mitrofanov 1981) as well as the frequency shift, it can be shown that the brightness changes by a fraction

$$\frac{\Delta B}{B} = -\frac{\Delta \nu}{\nu} \tag{5}$$

(note that Birkinshaw & Gull 1983 neglected the transformation of solid angle, and hence obtained a result in error by a factor -2).

The deflection angle δ is relatively large for a rich cluster of galaxies, about 1 arcmin. The transverse velocities of clusters of galaxies are unknown, but might be as large as 1000 $\mathrm{km\,s^{-1}}$ (Dressler *et al.* 1987). Then the peak-to-peak change in the brightness temperature of the microwave background radiation across a moving cluster of galaxies is

$$\Delta \mathrm{T} \approx 10\,(v/1000\ \mathrm{km\,s^{-1}}) \quad \mu\mathrm{K}. \tag{6}$$

Present observations of the microwave background radiation with single dishes achieve rms errors $\approx 30\ \mu$K, so that the signals from moving clusters should be measurable in the near future. The detectability of this effect is enhanced, however, by its unusual angular structure (Figure 3), and interferometric strategies may be effective for this reason.

Other moving masses, for example galaxies or cosmic strings, will produce a similar type of signal in the microwave background radiation. For a galaxy, the signal will be smaller by a factor $\approx 10^2$ in brightness, and will appear on an angular scale of a few seconds of arc. Although the angular scale is then a good match to the capabilities of interferometers such as the VLA, the sensitivity required to detect this signal is not available at present.

A moving string should produce a large step in the microwave background radiation (Kaiser & Stebbins 1984): for 1146+111B,C the brightness temperature change is $\Delta \mathrm{T} \approx 2\beta$ mK. Such signals should be detected easily using present single-dish techniques if $\beta > 0.1$. The absence of any such brightness signature in the region near the quasars 1146+111B and C was therefore interpreted as strong evidence against the interpretation of this system in terms of a cosmic string (Lawrence *et al.* 1986; Stark *et al.* 1986).

Figure 3. The frequency shift $\Delta\nu/\nu$ produced by a simple mass distribution. The contours are drawn at -1.0, -0.5, 0.0, 0.5 and 1.0 in units of $\frac{4GM}{r_0c^2}\gamma\beta\sin\alpha$, and negative and zero contours are drawn dashed. The small dotted circle represents the core radius of the mass distribution, and the vector indicates the direction of motion.

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