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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

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Astronomy

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Deflection of Light Rays in the Gravitational Fields of Galaxies

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It is known from the general theory of relativity that a ray of light, passing through the gravitational field of some body, is curved. Experimentally, this effect can be observed during a solar eclipse. In the present article the possibility is considered of observing the deflection of light rays in the gravitational fields of galaxies.

As light sources in these observations it is proposed to use screened galaxies. By screened galaxies, here and below, we shall mean galaxies G_1 (Fig. 1) situated in the solid angle formed by galaxy G_2 and the observation point P, and hidden from the observer by galaxy G_2. We shall agree to call screened galaxies that intersect the axis SP axial screened galaxies, and galaxies that do not intersect the axis SP off-axis ones.

Fig. 1

Let us assume that the space surrounding the galaxies under consideration is homogeneous (Galilean) space. The homogeneity of space is violated only in the regions where gravitational masses are located, and has a local, localized character. Let us consider the propagation of a light ray through regions of space in which homogeneity is violated. In order to observe the screened galaxy G_1 from the point P (Fig. 1), it is necessary that the light ray G_1L be deflected in the gravitational field of G_2 through an angle φ.

Solving the equation for the trajectory of a light ray in a gravitational field ([1])

Fig. 2

Figure 2: Fig. 2

$$\left(\frac{dr}{d\psi}\right)^2 = \frac{1}{b^2}(r+\alpha)^4 - (r+\alpha)(r-\alpha), \tag{1}$$

where r and ψ are polar coordinates in the Euclidean plane; b is the distance from the center of the source of the inhomogeneity of space to the trajectory of the light ray; $\alpha = \gamma M/c^2$; γ is the gravitational constant; M is the mass of galaxy G_2; c is the speed of light, we find the angle φ

$$\varphi = 4\alpha/b. \tag{2}$$

The condition for the ray SL to arrive at the point P is written in the form

$$\frac{4\alpha}{a_2(1+k)} = \delta^2, \tag{3}$$

where $k = a_2/a_1;\ a_2 = G_2P;\ a_1 = G_1G_2;\ a_1 = \dfrac{a_2}{4\alpha/a_2\delta^2 - 1}$.

If the distance $a_1 \gg a_2$, then expression (3) is written in the form

$$4\alpha/a_2 = \delta_{\text{cr}}^2;$$

δ_{cr} is the maximum (critical) angle at which an infinitely distant axial screened galaxy can be observed.

If the shielding galaxy has a spherically symmetric gravitational field (for example, belongs to type E0, E1, or S0 with a small degree of flattening), then the axial shielded galaxy will be observed in the form of a ring around the shielding galaxy. Similarly, one may write the condition necessary for observing off-axis shielded galaxies (Fig. 2):

$$\frac{4\alpha}{a_2(1+k)} = \delta^2 + \theta\delta. \tag{3*}$$

In this case the off-axis shielded galaxy will be observed in two diametrically opposite directions, relative to the shielding galaxy, lying in the plane passing through the point of observation and the galaxies G_1 and G_2.

Fig. 2

Let us investigate whether relations (3) and (3*) are satisfied at distances accessible to modern telescopes. First of all, let us determine the minimum distance to the shielding galaxy, starting from which observation of axial shielded galaxies is possible. The minimum distance will be determined by the value of the critical angle δ_{cr}, as well as by the angular radius of the shielding galaxy. The minimum value a_2 can be found from the relation $\delta_{\mathrm{cr}} - \delta_2 \geqslant 0$, where δ_2 is the angular radius of the shielding galaxy. For an axial galaxy $a_2 = r_2^2/4\alpha$, where r_2 is the radius of the shielding galaxy. For a shielding galaxy with mass $3 \cdot 10^{11} M_{\odot}$ and radius 4 kpc, the minimum distance will be $2.8 \cdot 10^8$ pc. When observing off-axis galaxies, the minimum distance will be considerably smaller.

In all the preceding arguments we did not take into account the resolving power of the telescope. Meanwhile, it is quite obvious that observation of shielded galaxies is possible only if the angular distance between the visible position of the shielded and shielding galaxies is greater than or equal to the smallest angular distance ψ_1 that can still be resolved by the telescope. In this connection, for a resolvable observation of shielded galaxies it is necessary that the condition

$$\delta \geqslant \delta_2 + \psi_1.$$

be satisfied. The minimum distance a_1, starting from which separate observation of axial shielded galaxies from the shielding ones is possible, for a given distance a_2, is written in the form

$$a_1 = \frac{a_2}{4\alpha/a_2\delta^2 - 1} + \frac{r_1}{k\delta}, \qquad (4)$$

where $\delta = \delta_2 + \psi_1$, r_1 is the radius of the shielded galaxy.

The maximum admissible distance a_2, at which observation of shielded galaxies is still possible, is determined by diffraction of the incident radiation at the entrance aperture of the telescope and can be found from the expression

$$a_{2\,\max} = \alpha/\psi_1^2.$$

For a shielding galaxy with mass $3 \cdot 10^{11} M_{\odot}$ and a telescope with mirror diameter 60 cm, the maximum admissible distance is $a_2 = 1.9 \cdot 10^{10}$ pc, i.e., it substantially exceeds the range of modern telescopes.

When considering the possibility of observing screened galaxies, one must take into account phenomena associated with atmospheric turbulence. Owing to atmospheric turbulence, the image of the object under study is blurred and considerably exceeds the size of the image that would be observed in the absence of turbulence.

Let us estimate the real possibility of observing screened galaxies with the instruments available to astronomers. Let a denote the distance from the observer to the screened galaxy, $a = a_1 + a_2$. The dependence of a on the distance a_2 is shown in Fig. 3. The value of a_2 corresponding to the minimum distance a is

Fig. 3

Figure 3: Fig. 3

determined from expressions (3), (3*) and (4). For an off-axis position of the screened galaxy,

$$a_2 = \frac{2Tr_2^2}{4\alpha - (2-\nu)r_2\psi_1},$$

where $\nu = \theta/\delta_2$, $T = 1-\nu$; for an axial position,

$$a_2 = \frac{r_2^2}{2\alpha - r_2\psi_1}.$$

If the finite angular dimensions of the screened galaxy are taken into account, the expression for a_2 is determined from the equation

$$(16\alpha^2 + 4\alpha r_1\psi_1 - 8\alpha r_2\psi_1 - r_1r_2\psi_1^2)a_2^2 - (8\alpha r_2^2 + 2r_1r_2^2\psi_1)a_2 - r_1r_2^3 = 0.$$

Fig. 3

Observation of screened galaxies is possible only if they are at distances not exceeding the operating radius of the telescope. Table 1 gives the minimum distances to axial and off-axis screened galaxies, calculated with and without allowance for phenomena associated with atmospheric turbulence. The latter case may be realized when observations are carried out beyond the Earth' s atmosphere, for example from Earth satellites.

Table 1

Diameter of telescope mirror, cm	a, pc	ν	M_{pg} of screened galaxy	m_{pg} of screened galaxy, with correction for red-shift	Mass of screening galaxy, in $M_{\odot}$	r_1, pc	r_2, pc	Image quality, in points	φ
With allowance for atmospheric turbulence									
500	$5.4 \cdot 10^9$	0	−20.0	–	$3 \cdot 10^{11}$	$4 \cdot 10^3$	$4 \cdot 10^3$	4	–
500	$5.8 \cdot 10^8$	0.7	−18.4	21.06	$3 \cdot 10^{11}$	$4 \cdot 10^3$	$4 \cdot 10^3$	4	–
When observing beyond the Earth's atmosphere									
100	$1.9 \cdot 10^9$	0	−20.0	23.48	$3 \cdot 10^{11}$	$4 \cdot 10^3$	$4 \cdot 10^3$	–	$2'',72$
60	$3.9 \cdot 10^8$	0.7	−20.0	18.41	$3 \cdot 10^{11}$	$4 \cdot 10^3$	$4 \cdot 10^3$	–	$2'',72$
60	$8.26 \cdot 10^8$	0.4	−20.0	20.51	$3 \cdot 10^{11}$	$4 \cdot 10^3$	$4 \cdot 10^3$	–	$2'',72$
100	$2.63 \cdot 10^9$	0.7	−20.0	25.03	$6.5 \cdot 10^{10}$	$4 \cdot 10^3$	$4 \cdot 10^3$	–	$0'',57$

Diameter of telescope mirror, cm	a, pc	ν	M_{pg} of screened galaxy	m_{pg} of screened galaxy, with correction for redshift	Mass of screening galaxy, in $M_{\odot}$	r_1, pc	r_2, pc	Image quality, in points	φ
100	$3.65 \cdot 10^8$	0.7	−18.4	19.81	$3 \cdot 10^{11}$	$4 \cdot 10^3$	$4 \cdot 10^3$	–	$0'', 57$

Comparing the operating radius of modern telescopes with the minimum distances to screened galaxies given in Table 1, we see that under terrestrial conditions it is possible to observe only off-axis screened galaxies, while when observations are carried out beyond the Earth' s atmosphere, both axial and off-axis screened galaxies will be accessible for observation.

Let us consider the case in which galaxy G_1 is located at the boundary of the screening region (Fig. 4). In this case galaxy G_1 will be visible to an observer located at P, not in the direction $S'P$, but in the direction LP, which makes an angle δ with the true direction. As a result, around galaxy G_2 there should be observed a region of avoidance for unscreened galaxies, i.e. a region free of galaxies.

Knowing the mass of galaxy G_2 and its distance from the observer (for example, from the radial velocity), one can use formula (3^*) to determine the width of the avoidance region.

Fig. 4

of avoidance. Table 2 gives the width of the avoidance region for galaxies with mass $3 \cdot 10^{11} M_{\odot}$, diameter 8 kpc, and various values of the distances a_1 and a_2. We see that as the distance a_1 decreases, the avoidance region decreases and, in the limit, tends to zero. When observing galaxies in clusters, the avoidance region should practically be absent.

Table 2

a_1, pc	a_2, pc	Angular width of the avoidance region
∞	10^5	$2''.96$
∞	10^8	2.68
10^{10}	10^8	2.65
10^9	10^8	2.40

a_1, pc	a_2, pc	Angular width of the avoidance region
10^8	10^8	1.29
10^7	10^8	0.26
10^5	10^8	0.003

Let us turn to a discussion of a method by which the detection of screened galaxies is possible. Axial screened galaxies will be observed in the form of a ring around the screening galaxy. Therefore their separation from the general field of galaxies presents no difficulty.

The situation is considerably more complicated with the separation of off-axis screened galaxies. The latter will be observed in the form of close double and multiple galaxies. It is necessary to find some way of distinguishing them from the multitude of observed double and multiple galaxies, which are formed both by physically and optically multiple galaxies and by screened galaxies. From the definition of the avoidance region given above it follows that screened galaxies can be observed only inside the avoidance region of the screening galaxy. In connection with this, the following method for detecting off-axis screened galaxies may be proposed.

Having determined, by one of the existing methods, the distances to the components of the galaxy system under study, from formula (3^*) it is easy to find the angle at which the distant galaxy would be seen in the absence of the screening galaxy,

$$\theta = \delta_\text{n} - \frac{4\alpha}{a_2(1+k)\delta_\text{n}},$$

where δ_n is determined from observations (Fig. 2),

$$\delta_\text{n} = \delta + \theta.$$

If $\theta < \delta_2$, then the galaxy under consideration is screened.

The observation of screened galaxies may be hindered by dust matter around the screening galaxy. However, according to currently available data, the types of screening galaxies considered by us do not contain dust matter ([2]). Screened galaxies may also be observed when they are screened by galaxies whose gravitational field does not possess spherical symmetry.

In conclusion, let us note that the questions considered in this article may find application in extragalactic astronomy and in the experimental verification of the general theory of relativity.

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CITED LITERATURE

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2. M. S. Eigenson, *Extragalactic Astronomy*, Moscow, 1960.

Note: Figure translations are in progress. See original paper for figures.