Observational physics of the mirror world

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The existence of mirror (or shadow) particles, which have only a gravitational and, possibly, a superweak interaction with ordinary matter and their own mirror interaction, is required in physics to restore symmetry between left- and right-handed coordinate systems. The investigation of such particles is possible only in astronomical observations. A qualitative analysis is given of an extensive range of phenomena that are due to the gravitational interaction between mirror objects and objects of ordinary matter. A program is suggested for searches for astronomical manifestations of mirror matter on scales from stars to superclusters of galaxies.

1. INTRODUCTION

A characteristic feature of current models of superstring theory, treated as a unified theory of all fundamental interactions, is the existence of an entire world of shadow particles, which interact with each other and do not possess any common interactions with ordinary particles except for the gravitational interaction.[1,2] The existence of the shadow world is a necessary condition in superstring theory, compensating for the asymmetry between the left- and right-handed states of ordinary particles. If the compactification of additional dimensions preserves the symmetry between left- and right-handed states, then the shadow world turns out to be a mirror world of particles and their interactions, the properties of which are completely symmetric to the respective properties of ordinary particles.[3,4] Because of the strict symmetry in the physics of ordinary and mirror particles, an analysis of the cosmological evolution of mirror matter enables one to draw very definite conclusions about the possible manifestations of mirror particles in the universe.[5-8]

In the present paper we give a qualitative analysis, more general than that in Refs. 5-8, of possible astronomical manifestations of mirror matter in order to expand to the maximum the search for effects of the mirror world in astronomical observations, which are the only means of testing the existence in nature of mirror twins of ordinary particles.

2. PHYSICS OF MIRROR PARTICLES

By construction, every ordinary particle (photon, electron, leptons, quarks, gluons, W and Z bosons, etc.) has an associated mirror twin. The interactions between mirror particles are strongly symmetric to the interactions between their corresponding ordinary particles. An analysis of mirror and ordinary particles in the same spacetime leads to coincidence of their gravitational properties. (Questions of a difference between their gravitational properties and of the existence of mirror and ordinary particles in different spacetime ordinary particles in different spacetime continua as a possible solution to the problem of the cosmological constant have been discussed in Ref. 9.)

We assume that no other interaction between mirror and ordinary particles exists besides gravity, and we exclude from consideration oscillations of ordinary particles into mirror particles and vice versa,[10] corresponding to the mixing of mirror and ordinary quantum states, as well as the existence of particles possessing both ordinary and mirror interactions: mirrons[11] and fractons.[12]

The strict symmetry between the properties of ordinary particles and their mirror twins means the equality of their masses, spins, and the constants of the respective interactions. For example, an ordinary electron is associated with a mirror electron, a particle with spin 1/2, the mass of which equals the electron mass, and the charge of its interaction with the mirror electromagnetic field equals the electric charge of the electron in magnitude. The mirror electron is electrically neutral – it has no interaction with ordinary photons – and mirror photons, with which a mirror electron interacts, do not interact with ordinary charged particles, passing freely through ordinary matter. Ordinary nucleons are to be compared with mirror nucleons, which form mirror nuclei. Mirror nuclei and mirror electrons comprise atoms of mirror matter, which can form all the same structures as atoms of ordinary matter.

Modern theory explains the masses of particles by their interaction with a scalar Higgs field, which violates gauge symmetry (see, e.g., Ref. 13). Equality of the masses of ordinary particles and their mirror twins means the strict equality of all the parameters of ordinary and mirror Higgs fields.

3. MIRROR PARTICLES IN THE EARLY UNIVERSE

a) Inflation and constraints on domain structure. According to current concepts, the global characteristics of the observable part of the universe – its homogeneity, isotropy, and "flatness" – are determined by the existence in the very early universe of a stage of exponential expansion (inflation). In the context of inflationary cosmology, at the conclusion of inflation the universe was reheated and its subsequent evolution corresponded to the scenario of a hot Friedmann model. The ratio between the densities of ordinary and mirror matter obtained in the transition to the Friedmann stage of expansion depends on the ratio of the probabilities of the creation of ordinary and mirror particles during heating of the universe. If on an energy scale $F >> 100$ GeV there is an interaction that accomplishes a conversion between ordinary and mirror particles, then, assuming the cross section of such conversions in units $\hbar = c = 1$ to be

$$\sigma(T)=\begin{cases}\gamma/T^2 & T>F\\ \gamma T^2/F^4 & T<F\end{cases},\quad \text{where } \gamma<1,$$

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we find that the rate of establishment of equilibrium between ordinary and mirror particles, $n\sigma v \approx T^3\sigma$, exceeds the rate of expansion of the universe, $\sim T^2/m_{pl}$, only for $F < \gamma m_{pl}$ and for heating of the universe to a temperature $T_p > (F/\gamma m_{pl})^{1/3}F$. Here $m_{pl} = (\hbar c/G)^{1/2} \approx 10^{-5}$ g is the Planck mass. Under these conditions, regardless of the mechanism of inflation, at its conclusion the reheating of the universe leads to equilibrium and symmetric distribution of ordinary and mirror particles. If these conditions are not satisfied, then an equilibrium ratio between the densities of ordinary and mirror particles can occur if the decay of the inflaton field occurs due to an interaction that is common to ordinary and mirror particles – specifically, the gravitational interaction.

The latter definitely occurs if the inflation is due to R effects in the polarization of the gravitational vacuum, or if an inflaton has the same interaction with ordinary and mirror particles. If the decay products of an inflaton have a distinct chirality, then symmetry between ordinary and mirror particles requires the existence of a mirror twin of such an inflaton.

In the chaotic inflation model,[14] we must evidently expect a difference in the random amplitudes of the inflaton fields, resulting in the formation of a domain structure in the distribution of ordinary and mirror matter.[15] Where the amplitude of an ordinary inflaton is greater than that of a mirror inflaton, at the conclusion of inflation ordinary particles will dominate and the admixture of mirror particles will be exponentially small (and vice versa for the opposite ratio of inflaton amplitudes).

Since inflation generally encompasses domains that considerably exceed the domain inside the current cosmological horizon, this case would correspond to an exponentially low density of mirror matter in the observable part of the universe. If an inflaton does not have a definite chirality, and equal amounts of ordinary and mirror particles have been created by the conclusion of inflation, then a domain structure could be formed by random local asymmetry in the amplitudes of ordinary and mirror scalar fields in different periods following the general inflation, in periods of phase transitions, in particular. The scale of such a domain structure depends on the specific parameters of the fields[15] and may be considerably less than the size of the current horizon. In this case, an analysis of the effects of "leakage" of ordinary matter into mirror domains on the density of light elements, as well as the spectral and spatial characteristics of the microwave background radiation, will indicate the possible scale of the structure. This scale either must be considerably less than the size of the horizon in the nucleosynthesis period or must considerably exceed the size of superclusters of galaxies.

The case of small scales of the possible structure ($M = << M_\odot$) will hardly differ in its cosmological manifestations from the case of initially uniform mixing of ordinary and mirror matter, which was considered in Refs. 5-8. Possible large-scale mirror domains ($M \geq 10^{16} M_\odot$) would appear as giant voids in the distribution of ordinary matter and, in a very special particular case, could result in an "island" model of the universe.[16,17] The observed isotropy of the microwave background radiation does not rule out the case in which the current outer boundary of the mirror domain lies beyond the cosmological horizon, but it rules out a structure for such domains on scales[15]

$$l_H(t_{rec})\sqrt{1+z_{rec}} < l < l_H, \tag{1}$$

where $l_H(t_{rec})$ is the size of the horizon in the recombination period at $z = z_{rec}$ and l_H is the size of the current horizon.

b) Baryon synthesis and the possible nonuniform distribution of mirror baryons. The introduction of a mirror world was dictated by the need to provide for equivalence between left- and right-handed coordinate systems in the presence of CP-violation in the world of ordinary particles.[4] For mirror particles the effects of CP violation are equal in magnitude and opposite in sign to the corresponding effects for ordinary particles. The generation of an excess of baryons in baryon synthesis of ordinary particles[18,19] therefore corresponds completely symmetrically to the generation of exactly the same excess of mirror antibaryons. Since the concept of baryon number for mirror particles is arbitrary, however, we shall speak of a baryon excess in the case of either chirality.

Local processes of generating a baryon excess in the very early universe in the symmetric evolution of mirror and ordinary matter lead to the simultaneous formation of early baryon excesses in the ordinary and mirror matter. In the absence of a domain structure in the universe, equality is established between the local densities of the ordinary and mirror baryons which have formed, and in the presence of a domain structure, one can expect strict equality in both the characteristic scales of the domains and the mean densities of ordinary and mirror baryons. If the formation of a baryon excess is not associated with CP violation effects in the nonequilibrium local processes for ordinary and mirror particles, then an interesting new possibility arises for "entropy" perturbations in the density of excesses of ordinary and mirror baryons, on arbitrary scales, generally speaking.

The mechanism[20] of baryon synthesis in supersymmetric Grand Unification models, which explains the baryon asymmetry of the universe by the existence of condensates of scalar quarks and leptons, may result in inhomogeneities in the distribution of excesses of mirror and ordinary baryons. If the densities of ordinary and mirror relativistic particles are equal, then any scales of such inhomogeneities turn out to be possible. In contrast to the mirror domains considered in (a), in which the densities of both baryons and radiation are exponentially suppressed, in the domains with an enhanced density of mirror baryons being considered here, only the density of ordinary baryons is low, while the radiation density is equal to the average. This case of entropy perturbations of density is consistent with the formation of astronomical objects – baryon islands of fixed chirality – up to the scale of the present horizon.

c) Nucleosynthesis and the mirror world. It should be noted that in all other cases except for the large-scale inhomogeneous distribution of mirror particles, the existence of relativistic mirror particles (mirror photons, electron–positron pairs, right-handed neutrinos, and left-handed antineutrinos) in the period of nucleosynthesis results in an increase in the primordial abundance of helium ^{4}He to $Y_{prim} \approx 29\%$ (Refs. 5-8, 21, and 22). On the basis of the radical limit $Y_{prim} < 25\%$, widely used in the literature, one can then conclude[22] that uniform mixing of mirror and ordinary matter is ruled out by the observations. Bearing in mind, however, that the observed mean ^{4}He abundance $Y \approx (28 \pm 12)\%$ is not in itself inconsistent with predictions of the mirror-world

TABLE I. Possible Manifestations of Interactions between Mirror and Ordinary Astronomical Objects on Different Scales

M objects	O objects							
	cluster of galaxies	galaxies	globular clusters	open clusters	stars	relativistic objects	diffuse gas in the Galaxy	molecular clouds
I Clusters of galaxies	1-I k, g	2-I k					7-I k	
II Galaxies		2-II k	3-II k				7-II g	8-II k
III Globular clusters			3-III k	4-III k	5-III k	6-III k	7-III g	8-III g, k
IV Open clusters								
V Stars					5-V g, k	6-V g, k	7-V g	8-V g
VI Relativistic objects					5-VI g, k	6-VI k	7-VI g	8-VI g
VII Diffuse gas in the Galaxy					5-VII g	6-VII g		
VIII Molecular clouds				4-VIII k	5-VIII g, k	6-VIII g, k	7-VIII g	8-VIII k

Note. The first number corresponds to the type of object that lies in the gravitational field of its mirror partner; the letters g and k mark gas-dynamic and kinematic effects, respectively (see text). 1-I k) normal cluster of galaxies in a mirror cluster (kinematics): the velocity spread is determined by the mirror mass (dark matter), and with relative motion of the mirror and normal clusters, distortion of the mass distribution in the normal cluster is possible; 1-I g) normal cluster of galaxies in a mirror cluster (gas dynamics): localization of hot gas not in the vicinity of the center of the cluster but in the vicinity of the gravitational well of the mirror cluster, and gas entrainment effects; 2-I k) normal galaxy in a mirror cluster of galaxies (kinematics): anomalous velocity due to motion in the field of the cluster (galaxy with an anomalous red shift z); 2-II k) normal galaxy interacting with a mirror galaxy (kinematics): peculiar distortions of shape without a visible agent, and dark matter; distortion of the gaseous structure with the initiation of star formation; 3-II k) normal globular cluster in a mirror galaxy (kinematics): "runaway" globular clusters in the Galaxy and intergalactic space; 3-III k) normal globular cluster in a mirror globular cluster (kinematics): anomalous velocity spread of stars in the cluster, due to the dark matter of the second mirror cluster; 4-III k) normal open cluster in a mirror molecular cloud or globular cluster (kinematics): anomalous dark matter preventing the decay of open clusters; 4-VIII k, 5-III k) normal star or relativistic object in a mirror globular cluster (kinematics): capture of a normal object by a mirror globular cluster (runaway stars, high-velocity pulsars); 5-V k, 5-VI k) normal star interacting with a mirror star or mirror relativistic object (kinematics): binary stars lacking a visible normal component; 5-V g) normal star interacting with a mirror star (gas dynamics): accretion onto an unseen gravitating center with a gravitational well of finite depth, mirror mass present at the center of a normal star, altering the color–luminosity relationship, etc.; 5-VI g) normal star interacting with a mirror relativistic object (gas dynamics): strong accretion onto a gravitational potential well with a bottom and without energy release upon stopping at the surface of the object; 5-VII g) 6-VII g) normal star or relativistic object in a mirror interstellar medium (gas dynamics): accretion effects altering the mass and momentum of the normal object; 5-VIII k, 6-VIII k) normal star or relativistic object in a mirror molecular cloud (kinematics): capture of a normal object, appearance of anomalous velocity due to the dark matter of the cloud; 5-VIII g, 6-VIII g) normal star or relativistic object in a mirror molecular cloud (gas dynamics): accretion onto the normal object of dense gas from the mirror cloud with type 5-VII g and 6-VII g effects; 6-V k, 6-VI k) normal relativistic object interacting with a mirror star or relativistic object (kinematics): periodic variations in the period of normal pulsars in such pairs; 6-V g) normal relativistic object interacting with a mirror star (gas dynamics): accretion of the mirror star onto the normal pulsar, rapidly changing its mass and hence its period; 7-I k) similar to 2-I k; 7-II g) normal galaxy interacting with a mirror galaxy (gas dynamics): distortion of the gaseous structure with initiated star formation; 7-III g, 7-V g, 7-VI g, 7-VIII g) accretion of galactic gas into the potential wells of mirror globular clusters, stars, relativistic objects, and molecular clouds, respectively, with effects of type 5-VI g; 8-II k) capture of a molecular cloud by a mirror galaxy, appearance as a high-velocity molecular cloud at the periphery of or outside the galaxy; 8-III k) capture of a molecular cloud by a mirror globular cluster with effects in the velocity spread of the gas; 8-III g, 8-V g, 8-VI g) accretion of the gas of a molecular cloud into the gravitational wells of globular clusters, stars, and relativistic objects, with effects of type 5-VI g; 8-VIII k) capture of a molecular cloud by its mirror twin, manifested by dark matter and velocity spread in the cloud.

model,[21] and that the problem of the reliable independent model estimation of the possible primordial ^{4}He abundance does not seem conclusively resolvable at present,[1)] we shall adhere below to the basic outline of the scenario of cosmological evolution of uniformly mixed mirror and ordinary matter.[5-8]

4. FORMATION OF INHOMOGENEITIES OF MIRROR MATTER

According to the scenario of Refs. 5-8, in the radiation-dominated stage in the universe, equal densities of ordinary and mirror radiation and light neutrinos dominate, and there is a small admixture of equal densities of mirror and ordinary baryons (and possibly an admixture of equal densities of nonrelativistic ordinary and mirror particles such as mirror and ordinary photinos, mirror and ordinary axions, etc.).

At the conclusion of the radiation-dominated stage, nonrelativistic particles of dark matter, forming the large-scale structure, start to predominate in the universe. The specific choice of a model of structure formation is not important for most of the subsequent questions about the manifestations of mirror matter. Mirror baryons, the average density of which is strictly equal to the density of ordinary baryons, comprise a small admixture of nonrelativistic matter that participates in the overall development of gravitational instability. Here the scenario of structure formation is determined by the dark matter, which dominates in density. It is possible for mirror matter to affect the observable properties of such structure only for a large-scale domain distribution (with $M > 10^{16} M_\odot$) or island distribution of mirror baryons.

In the latter case, the baryon inhomogeneities can have any scale, and the formation of "pure" mirror objects on any scale is possible. Bearing this possibility in mind, manifestations of mirror objects on any scale are discussed below. A numerical analysis[23] shows that models of hot, unstable dark matter (massive unstable neutrinos in the simplest case) make it possible to reproduce fairly naturally the observed large-scale structure, whereas in models of cold dark matter such reproduction requires the physically unclear hypothesis of "biasing" in the distribution of visible matter and dark matter. A large-scale island distribution of baryons may play the role of the physical mechanism of complete biasing in the model of cold dark matter. Islands of mirror baryons would then look like voids, free of galaxies of ordinary matter. But the problem of rapid evolution of structure, characteristic of all models of stable, structure-forming dark matter,[23] evidently remains in this case.

For definitions, below we shall consider the "pancake" scenario of structure formation, the main features of which are retained by the cosmology of hot unstable particles. In the absence of an island or domain structure in the baryon distribution, the evolution of mirror inhomogeneities occurs in accordance with the scenario of Refs. 5-8. The fragmentation of ordinary and mirror matter into pancakes results in the formation, in the course of development of thermal instability, of gas–star complexes of definite chirality with a characteristic mass $M_* \approx 10^6\ M_\odot$. Depending on the conditions of pancake formation, M_* can be in the range 10^2-$10^9\ M_\odot$ (Ref. 5-8).

The spatial separation of inhomogeneities of ordinary and mirror matter that are uniformly mixed together on scales M_* is due to the fact that they have a small gravitational potential and a large velocity spread, and thermal instability develops independently in the ordinary and mirror gases. Within the developing complexes of a certain chirality, further fragmentation occurs in parallel with the hierarchical gravitational bunching – successively into galaxies and then into clusters of galaxies.

In this scenario, to within accretion effects, fragments that do not exceed globular clusters in mass are objects of a certain chirality, and in larger formations there are approximately equal average amounts of ordinary and mirror matter with symmetric distributions of the respective objects with respect to type, mass, and velocity.

In the Galaxy, in particular, there should be "local dark matter" with a density equal to the density of ordinary matter and with a symmetrical distribution with respect to objects. This prediction of the model of Refs. 5-8 agrees well with the data of Refs. 24 and 25. On the basis of this picture, supplemented by possible effects of an island distribution of baryons, let us turn to the expected observational manifestations of mirror matter on different astronomical scales.

5. MANIFESTATIONS OF MIRROR ASTRONOMICAL OBJECTS ON THE SCALE OF GALAXIES AND STAR CLUSTERS

From the foregoing it is clear that all the possible observational manifestations of mirror matter should be due only to its gravitational interaction with ordinary matter. The existence of mirror objects of any type is possible here.

Two types of manifestation can be identified from the most general viewpoint: the case in which only the gravitational interaction is considered and situations in which gas-dynamic effects are important. In the first case, the influence of mirror matter is manifested in the presence of peculiar velocities of ordinary objects. Effects of this kind can be called kinematic. They are manifested most clearly when an ordinary object lies in a gravitational field associated with a mirror configuration with a considerably larger mass. In the second case we are talking about effects originating in the influence of the gravitational field due to various types of objects on gas of the opposite chirality.

Various manifestations of the interaction of mirror and ordinary matter can be generalized with the help of Table I. The various effects originating in different combinations of objects are given in its cells. Below we consider in more detail some examples of the interaction of various types of objects of opposite chirality that could be detected, in our opinion.

a) Galaxies and clusters of definite chirality. For an island distribution of baryons on scales of galaxies or clusters of galaxies, these astronomical objects have a definite chirality. A possible admixture of ordinary matter in mirror galaxies or of mirror matter in ordinary galaxies may be related either to the presence of a small initial admixture, determined by a local asymmetry of chirality originating in the process of baryon synthesis (see Sec. 3b), or with the accretion of intergalactic gas onto them. The following observational effects of mirror galaxies and clusters of galaxies can be distinguished.

1) The capture of ordinary galaxies by a cluster of mirror galaxies is capable of leading to the appearance of objects with large peculiar velocities or of small groups of galaxies with an anomalous virial paradox having a velocity spread up to $(1\text{-}2)\cdot 10^3$ km/sec, typical of dense rich clusters.[26] The detection of a peculiar velocity component of a massive galaxy at the level $\geq 10^3$ km/sec is possible in principle by the methods suggested by Zel'dovich and Syunyaev[27] for measuring the peculiar velocities of clusters of galaxies, i.e., from distortions in the parameters of the microwave background radiation in scattering from the electrons in the gaseous corona of a galaxy. The probability of the capture of a galaxy by a rich cluster is apparently quite high. If we assume that the energy dissipation required for capture occurs in an encounter between the centers of galaxies at a distance of the order of the galaxy diameter d, then a cluster of N members with a diameter D will capture a background galaxy with probability

$$W = \pi d^2 \rho^2 /_6 D = 4N (d/D)^2 \approx 0.01\text{-}1. \quad (2)$$

Here ρ is the number density of galaxies in the cluster. The numerical estimate is given for a rich cluster with $N = 10^3$-10^4 and $d/D = 10^{-3}$-10^{-2}.

2) In the above-described process of capture by a mirror cluster of galaxies of ordinary matter, the latter must inevitably lose a considerable amount of gas. As a result, the scanty cluster of galaxies of ordinary matter that is formed in the potential well of the mirror cluster, in addition to a strong virial paradox, may turn out to possess a considerable amount of intergalactic gas (IGG). It will fill a region with a size that is typical of rich clusters. The amount and hence the density of the IGG should be less than that in rich clusters by a factor $k = \alpha N_m / N_o$, where N_m and N_o are the numbers of galaxies in the rich mirror cluster and of ordinary galaxies captured by it, respectively, and $\alpha < 1$ is a coefficient that allows for the fact that, in contrast to rich clusters of one chirality, no cooling flow (see the reviews Refs. 28-30) will be establish-

ed, nor will gas be lost from the cluster. For $N_o/N_m \approx 10^{-2}$, we can thus expect $k \gtrsim 0.03$ and an IGG emission measure $EM \approx k^2 \approx 10^{-2}$-$10^{-3}$ two or three orders of magnitude less than in the case of rich clusters of galaxies. The next generation of x-ray telescopes will make it possible to detect quasars up to a red shift[31] z = 5-10 and IGG in rich clusters up to z = 2-4. In the case expected here, therefore, the IGG may be detected at $z \approx 1$. The observation of hot IGG with no visible rich cluster of galaxies may become a strong argument for the existence of a mirror (shadow) world.

3) The interaction between ordinary and mirror galaxies results in distortion of their shapes. In an ordinary galaxy one should observe a perturbation in shape in the absence of a visible source of distortion. The development of numerical methods for calculating the tidal actions of galaxies on each other (see Refs. 32-34 and the reference therein) can be used to solve the inverse problem of determining the parameters of the perturbing body from the appearance of the distorted galaxy. In contrast to the case of perturbation by a single black hole of the same mass, the perturbation from a mirror galaxy is not accompanied by observational effects of accretion onto such a black hole. The corresponding accretion onto a black hole in the active nucleus of a mirror galaxy will be suppressed in proportion to the ratio of the mass of the nucleus to that of the entire galaxy ($\leq 10^{-2}$-10^{-4} for active galactic nuclei; see, e.g., Ref. 35).

4) In an ordinary gas-rich galaxy or in a protogalactic cloud of ordinary gas, the gravitational perturbation by a mirror galaxy may initiate a burst of star formation. As a result, the ordinary galaxy will be observed as irregular.

The phenomena described under numbers 3 and 4 in this section can be caused by gravitationally bound accumulations of dark matter, which may develop upon "biasing" in the distribution of dark matter with respect to baryons. A collisionless gas of particles of dark matter, however, cannot form the dense inhomogeneities typical of mirror matter that possesses dissipation mechanisms. We must therefore seek effects caused by mirror matter of moderate density, far from the manifestations of both black holes and very diffuse dark matter.

5) If the activity of a galactic nucleus is determined by the presence of a black hole of mass 10^6-10^{10} $M_\odot$, then symmetry in the properties of ordinary and mirror matter enables us to suggest the existence of such black holes in the nuclei of mirror galaxies, as well. In this case, mirror galaxies with active nuclei will be observed as single supermassive black holes, the observational manifestations of which will depend on the density of ordinary matter in their vicinity. As noted in Refs. 5-8, if mirror matter exists, the development of close pairs of supermassive black holes in galactic nuclei can be explained without forcing the issue.

6) Massive mirror galaxies can cause a gravitational lens effect without an optically observable source for such an effect.

7) Rapid motion of masses of mirror matter may be a source of gravitational waves that are not accompanied by other observational effects. (Supermassive black holes, also capable of producing gravitational radiation, may be detected from accretion effects).

8) The presence of gas of ordinary matter in a mirror galaxy will result in observable isolated gas clouds or low-mass galaxies having a large internal velocity spread, i.e., a large internal virial paradox. Intergalactic gas clouds may be possible candidates for such formations: in a number of nearby groups of galaxies, cold gas is found in the form of massive ($M > 10^8$ $M_\odot$) H I clouds[36] with sizes typical of galaxies: 20-25 kpc. The most massive H I cloud known is found in the G 11 group of galaxies in the constellation Leo near M 96 (Ref. 37). This cloud has a size of at least 100 × 30 kpc, an H I mass $M_{\rm H\,I} > 10^9$ $M_\odot$, and a density $n = 4\cdot10^{-4}h_{50}$ cm^{-3} [h_{50} = H/(50 km·sec^{-1}·Mpc^{-1})][38,39] The surface brightness of this cloud[40] in the visible is less than 30^m per square arcsec. Such clouds can show up in the absorption spectra of quasars.

b) Globular clusters of definite chirality. Let us turn to the case of separation of mirror and ordinary matter on the scale of globular clusters. Globular clusters are among the oldest astronomical objects, possibly originating before the formation of galaxies, from inhomogeneities with a scale 10^6 $M_\odot$, which are obviously objects of definite chirality, even given uniform mixing of ordinary and mirror matter[5-8] (see Sec. 4).

1) The capture of ordinary stars by a mirror globular cluster may result in the formation of an open cluster of ordinary stars that is capable of existing for a very long time without breaking up and which has a strong virial paradox. The chances for the formation of such objects by the capture of stars are greatest for mirror globular clusters that are moving near the galactic plane in an orbit with a fairly small eccentricity. The chances for an open cluster in the gravitational field of a mirror globular cluster are greater, however, if the open cluster originates from gas trapped by the mirror globular cluster at the time of separation of matter. According to Refs. 5-8, the fraction of the gas admixture of different chirality in this case is expected to be $\sim 10^{-2}$.

The characteristic decay time of normal open clusters is[41] (1-3)·10^8 years, whereas such a cluster formed in the potential well of a mirror globular cluster may have an age $t \cong 10^{10}$ yr. Several such old open clusters are observed in the Galaxy. The age of NGC 188 is estimated to be (5-10)·10^9 years (Refs. 42 and 43), for M67 it is (5 ± 0.5)·10^9 years (Ref. 44), for NGC 752, 2·10^9 years (Ref. 45), and for NGC 2243 and Mellotte 66, 6·10^9 years (Ref. 46). A detailed analysis of these clusters in terms of the mirror world hypothesis would be of interest.

Stars captured by a mirror globular cluster can have different ages, in contrast to those in ordinary open clusters. This fact should be taken into account in determining the affiliation of stars with such an open cluster.

2) In the capture of an ordinary star by a mirror globular cluster or of a mirror star by an ordinary globular cluster, close binary star systems having components of different chirality can be formed. A typical feature of such systems is the presence of a nonrelativistic unseen companion. In cases in which gaseous clumps of ordinary and mirror matter that generate globular clusters lie close to each other or in the same region of space, a mixed globular cluster may be formed. In addition to the obvious virial paradox, in a compact mixed globular cluster of radius R containing N stars, according to the estimate of Refs. 47 and 48,

$$N_{bin} \approx 3\cdot(N/10^5)^{1.5}\cdot(R/5\ \mathrm{pc})^{-2.5}\cdot(t/10^9\ \mathrm{yr})$$

stellar pairs may be formed in a time t due to tidal dissipation in close encounters between stars. For $N = 2 \cdot 10^5$, $R = 5$ pc, and $t = 10^{10}$ yr, we have $N_{bin} = 60$, half of which will be of mixed chirality.

c) Manifestations of mirror matter in clouds of ordinary molecular gas. Giant molecular clouds are the most common of the massive unitary objects in galaxies. While their mass is about that of a globular cluster, the number of these clouds in the Galaxy is an order of magnitude greater than the number of globular clusters.[49] In a Galaxy consisting of comparable amounts of mirror and ordinary matter, therefore, mirror and ordinary clouds should pass through each other fairly often. Molecular clouds contain a large number of internal inhomogeneities (regions of enhanced density) that are under conditions close to incipient gravitational instability. The structure of star-forming regions shows that a relatively weak perturbation can initiate star formation inside molecular clouds. Shock waves are the usual trigger for star formation, as a consequence of which the youngest objects are located in a thin outer layer of a molecular cloud.[50] The passage of a massive body through a molecular cloud is obviously also capable of initiating star formation, in which case the star-forming region will be determined by the spatial distribution of the gravitational perturbation and may occupy a considerable part of the cloud volume.

In the case of comparable amounts of ordinary and mirror matter in a galaxy being considered here, the source of such perturbations will primarily be mirror molecular clouds and, somewhat less often, mirror globular clusters. Since molecular clouds collide with each other at low relative velocities (~10 km/sec) and are strongly dissipative objects, in a collision an ordinary and a mirror cloud may form a giant in a collision an ordinary and a mirror cloud may form a giant molecular cloud that is mixed in chirality, inside which there is an increased probability of the formation of stars of mixed chirality and of pairs of stars of opposite chirality.

In repeated gravitational interactions between stars and inhomogeneous of molecular clouds, some stars may be trapped by the molecular clouds, which should greatly increase the accretion of interstellar gas onto such stars. This effect may increase the rate of gas accretion onto a star of opposite chirality.

6. EFFECTS OF MIRROR MATTER AT STELLAR SCALES

1) The analysis in Refs. 5-8 of the accretion of interstellar gas by a star of the opposite chirality led to an estimate of $\Delta M \approx 10^{-6}$-$10^{-7}\, M_\odot$ for the admixture of matter of different chirality in the stars.

If such a mirror admixture in the sun forms a mirror planet near its surface, then this, according to Refs. 5-8, could explain the source of solar oscillations with a period $T \cong 160$ min (Ref. 51). V. F. Shvartsman drew our attention to the possibility of observing the accretion of ordinary interstellar gas by a single mirror neutron star.

2) The revolution of an ordinary neutron star and an admixture of mirror matter about their common center of mass should result in periodic variations in the pulsar period due to the Doppler effect. In contrast to the analogous effect from difficult-to-observe planets of ordinary matter, the variations due to mirror matter can have a period corresponding to small orbits that could not be formed by ordinary planets or preserved during a supernova explosion. High-precision timing of pulsars over times of less than several hours are needed to search for such effects.

3) In the accretion of ordinary gas and dust by a mirror star in the interstellar medium, a disk of the protoplanetary type will be formed, at the center of which there will be no young star. Such disks can be observed in the 2.6-mm CO radio line. From the Doppler effect one can determine the mass of the central configuration, which will be at sharp variance with the low luminosity of the central body.

Accretion in regions of enhanced density of gas of different chirality and the formation of binary systems consisting of ordinary and mirror stars open up new possibilities for searches for mirror matter. Binary stars of opposite chirality can originate not only inside a globular cluster (Sec. 5b), but also in star formation as giant molecular clouds of different chirality pass through each other (Sec. 5c).

4) A mixed star, consisting of comparable amounts of ordinary and mirror matter, can be formed in the process of star formation or as a result of the evolution of a pair of stars of opposite chirality. The relationships among the main stellar characteristics – mass, radius, luminosity, colors, effective temperature, etc. – can be strongly disturbed for the ordinary matter in a mixed star. Such stars should occupy an unusual position on the Hertzsprung–Russel diagram, in particular. In the case of a supernova explosion in the mirror matter of a mixed star, a reorganization of its gravitational field occurs, which must necessarily be accompanied by reorganization of its structure and a simultaneous change in the properties of the optically observed object. The size of such a star evidently must increase and its surface temperature must decrease.

5) In close pairs of stars of different chirality, the accretion of ordinary matter into the potential well produced by the mirror star should create an accretion disk without an observable accreting center. In the case of a nonrelativistic mirror star, in which the potential well has a relatively "flat" bottom, we should expect the formation of a geometrically thick accretion disk or a spheroidal gaseous formation in place of the companion of the ordinary star. At the rates of mass transfer typical of close binary stars, such disks should be optically thick with an appearance typical of highly aspherical stars. One promising method of studying such formations is to analyze the linear polarization of their radiation.[52,53] With a low-mass normal companion, such a disk should remain very cool, most likely being an infrared source of low luminosity, which would be at sharp variance with the value of the "disk mass" determined from the Doppler effect, equal to the mass of the mirror star.

In a detached pair of stars of different chirality, there may be no noticeable accretion onto the nondegenerate mirror star. Such a star may be detected as an unseen massive companion to a star.

An estimate of the relative fraction of systems with different chirality among binary stars can be obtained from data in existing catalogs of spectroscopic binaries. In the catalogs Refs. 54-56, for example, the physical characteristics and orbital elements of about 1500 spectroscopic binaries are given. In 45 of them the mass of the secondary component is

$M_x > 3\ M_\odot$ (their mass function is $f(M) > 3\ M_\odot$).[2)] Lines of the secondary component have not yet been detected in only 6 of these 45 systems. With allowance for the fact that more careful searches may yet reveal the fainter secondary star in these binaries, and that there may be black holes among the unseen components, a conservative estimate of the fraction of binaries containing mirror components is $\alpha < 6/45 = 13\%$.

In the Appendix we give the characteristics of these six spectroscopic binaries and a brief discussion of observational tests for choosing between the alternatives of a black hole and a massive mirror star as the secondary component.

6) In the flow of ordinary matter onto a mirror white dwarf or mirror neutron star in a binary system, a condensation with the characteristic size of the corresponding accreting mirror star or of its dense core, the size of which is an order of magnitude less than the size of the entire star, may be formed at the center of the accretion disk. The observational manifestations of such a condensation will be close to the manifestations of ordinary degenerate stars with some quantitative differences (a possible smaller size and higher temperature).

In the case of a mirror white dwarf, moreover, in its place one will observe a predominantly hydrogen object, in which detonation may result in events like a nova outburst, obviously with somewhat altered quantitative characteristics. In the case of a mirror neutron star one may observe burster-type events, the quantitative parameters of which may also differ from the usual.

An ordinary neutron star paired with a normal mirror star will be observed as a radio pulsar in a binary system with an unseen companion. It can be distinguished from a system of two ordinary relativistic stars by the change in the orbit of the binary system, many orders of magnitude faster than in the emission of gravitational waves. Such evolution may be a consequence of a) motion of the line of apsides due to the finite size of the normal component; b) accretion of mirror matter from the normal component onto the observed neutron star; c) mass loss from the system in nonconservative mass transfer or for other reasons.

7. CONCLUSION

The qualitative analysis of the observational manifestations of mirror matter in the present paper considerably expands the possibilities in the astronomical search for a mirror world in comparison with the results of Refs. 5-8. The development of modern superstring theory, in which the existence of a mirror or shadow world is a rigorous fundamental prediction, imparts special relevance to such a search. In this connection, it should be noted that many of the effects indicated here do not require strict symmetry between the properties of ordinary and mirror matter and remain valid in the case of dissipating shadow matter. The absence of effects of mirror matter in observations may therefore not only mean the observational refutation of the mirror world hypothesis but also serve as a limit on the possible properties of the shadow world, thereby providing important "experimental" material for the development of the theory of elementary particles in a realm accessible to direct laboratory verification. On the other hand, the discovery of such effects – the importance of which it would be difficult to overestimate – would make it possible to draw a conclusion from their aggregate about the symmetry of physical laws for visible and invisible matter. Since the search for a mirror world is possible only by means of its gravitational action, and since such action on the scales of galaxies and clusters of galaxies may also be caused by the presence of a gas of collisionless particles of dark matter, scales smaller than galaxies are the most suitable for a "clean" determination of the effect of a mirror world. On geometrical scales smaller than the size of normal stars, however, the manifestations of mirror matter are difficult to distinguish from the similar manifestations of black holes. Phenomena occurring in regions 10^{10}-10^{20} cm in size – from the size of nondegenerate stars to the size of giant star clusters, associations, and gas–dust complexes – are therefore optimal for the search for a mirror world. The search for effects of mirror matter on other scales is nevertheless of general astrophysical importance, stimulating the search for new astronomical phenomena. From the timeliness and importance of the problem and the existence of observational possibilities for its solution, it follows that the development of cooperative programs of astronomical search for effects of a mirror world would be appropriate.

APPENDIX

In Table AI we give the characteristics of six spectroscopic binaries from general catalogs,[54-56] for which the mass function is $f(M) > 3\ M_\odot$ but lines definitely belonging to the secondary component have not yet been detected. From the definition of the mass function, $f(M) = M_2 \sin^3 i/(1 + M_1/M_2)^2$, we have

$$M_2 = f(M)\,(1+M_1/M_2)^2/\sin^3 i > f(M) > 3M_\odot.$$

TABLE AI. Spectroscopic Binary Systems with an Invisible Massive Secondary Component

System	Brightness in the Y band (magnitude) and spectral type	Period of revolution, days	Radial velocity amplitude, km/sec	Mass function $f(M)$, $M_\odot$
A 0620–00	18,2	0,323	457	3,18
HD 72754	6,9 B8 Ipe	33,7	137	9,0
HD 105998=W Cru	9 G1 Iab	198,5	65,7	5,82
HD 149881=V 600 Her	6,6 B0,5 III	5,2	21,4	5,2
HD 193928	6,8 WN 6	21,6	130	4,94
HD 235679	8,9	225,2	64	5,9

In none of these cases can the secondary component be either a white dwarf or a neutron star. If additional careful investigation of these systems reliably rules out a secondary component fueled by a central thermonuclear source, it will mean that either a black hole or a mirror star exists in the system.

The main criterion for choosing between these two alternatives should obviously be the total additional energy release in the binary system. In the case of a black hole, the energy release due to accretion from the visible component should be several orders of magnitude higher than for a mirror star. With allowance for the possible efficient screening of radiation by a thick accretion disk, it is the luminosity integrated over all wavelengths that must be considered.

In accretion onto a black hole, moreover, we should expect very rapid luminosity fluctuations with minimum times of the order of[58] $t = r_g/c$. In this context, the binary system A 0620−00, an x-ray nova with millisecond bursts,[59] must be a system containing a black hole rather than a mirror star.

In the W Cru and V 600 Her systems, for example, the lower limits on the mass of the unseen components are 16 and 32 $M_{\odot}$, respectively. If the secondary components are not a black hole or a mirror star, their luminosities should then exceed the luminosities of the visible components.

[1)]In any case, an analysis of the astronomical manifestations of mirror matter with properties that are strictly symmetrical to those of ordinary matter makes possible simple qualitative estimates of such manifestations for the more general case of shadow matter for which symmetry of properties with ordinary matter is lacking.

[2)]The limit $M_x > 3\ M_{\odot}$ was chosen so as to eliminate systems containing low-luminosity white dwarfs and neutron stars. The theoretical upper limit to the mass of a neutron star is $\lesssim 3\ M_{\odot}$, according to Ref. 57.

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