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HALOS AROUND "BLACK HOLES"

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"Black holes" – bodies confined within their gravitational radius – will necessarily attract interstellar gas. If $M_{hole} > 0.03\ M_\odot$, at least $0.01\ mc^2$ of the infalling material should be converted into radiation. The corresponding luminosity would be of order $10^{32}\,(M/10\,M_\odot)^{3/2}\,(\rho_{gas}/10^{-24}\,g\cdot cm^{-3})^{1/2}$ erg/sec, and would result from synchrotron radiation by magnetized plasma that would be heated to $T \approx 10^{12}$°K during the infall process. The spectrum would have a very mild slope extending from optical to radio wavelengths. Black holes might be observable as faint optical stars with no lines; they could be distinguished by intensity fluctuations on a time scale $\Delta t \approx 10^{-5}$–10^{-2} sec, with no periodic component whatever. In many cases accretion by massive holes ($10 \lesssim M \lesssim 10^4\ M_\odot$) should engender hard radiation (x and/or γ rays) exhibiting a flare behavior on a time scale ranging from a few months to tens of years; the peak intensity should be 10-100 times the synchrotron intensity. This phenomenon is associated with the turbulence of the interstellar medium: the angular momentum of the gas would halt the infall near the gravitational radius of the hole, and the momentum would be "annihilated" when the object moves into the adjacent turbulence cell. Only if $M > 10^6\,M_\odot$ would the angular momentum of the gas be capable of diminishing the mass falling into an isolated hole (that is, its luminosity). During infall toward a hole of $M \approx 10^5\,M_\odot$, the gas will initially remain cool ($T \approx 5000$°K) and will display an emission spectrum similar to the optical spectra of quasars. Because of accretion, a hole in a binary-star system might be observable as a visible secondary component. Accretion by a hole can be distinguished observationally from accretion by a neutron star. Possible candidates for black holes that may actually have been detected include certain type-Dc white dwarfs, the γ-ray star Sgr γ-1, the x-ray flare stars Cen X-2 and Cen X-4, and such objects as Sco X-1 and Cyg X-2.

1. INTRODUCTION

Perhaps the most interesting implication of general relativity theory is the prediction that the universe may contain masses that are confined within their gravitational radius $r_g = 2GM/c^2$. To an external observer such objects should appear rather like "black holes," drawing matter and radiation into themselves. We will recall that although a collapsed body will of itself radiate nothing at all – neither light, neutrinos, nor gravitational waves – it will nevertheless possess a static gravitational field which will influence its surroundings. Matter that is drawn in will reach r_g only asymptotically, after an infinite time; the region $r < r_g$ could not be observed at all by an external observer, and would thereby "drop out" of our space [1].

How might "black holes" be formed? There are at least five ways:

1) holes may have been present in the universe "from the beginning," that is, left over from the epoch of singularity;

2) holes may have developed from density fluctuations during the prestellar stage;

3) holes may have formed from supermassive first-generation stars;

4) holes may have resulted from the relativistic evolution of close clusters, galaxies, and the like;

5) finally, holes may have developed from ordinary but sufficiently massive stars.

It is highly probable that this last possibility has been realized. The discovery of pulsars, as is

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now well recognized, has confirmed the old theoretical prediction that massive stars are unstable and should suffer a catastrophic collapse at the end of their evolution. But theory predicts two final states after collapse: a neutron star in the event that the mass of the object is less than 1.5 $M_\odot$; and an uninterrupted infall, or a "collapsed" star, if M > 1.5 $M_\odot$.

Neutron stars have been discovered because of their activity: the generation of relativistic particles and radio waves. Collapsed stars, however, are passive by their very nature. Consequently, it is usually considered that "black holes" might most likely be discovered through their influence on radiating matter: on the motion of the normal component in a binary star [2-4], on stars in globular clusters [5] or galaxies [6], on the motion of the galaxies themselves [7] and so on.

However, the method of the "excluded third" is risky in astronomy. And furthermore, when configurations with an invisible component are selected the objects sought might be left out of the list altogether. As we shall demonstrate in this paper, holes whose mass exceeds the solar mass ought to be surrounded by highly luminous halos.

The question of the energy released through accretion by collapsed bodies was first posed by Zel'dovich [8] and Salpeter [9]. The accretion of gas by "superholes" ($M > 10^7 M_\odot$) located at the centers of galaxies has been discussed by Lynden-Bell [10]. We shall be interested primarily in "stellar" masses, with $10^{-1} M_\odot \lesssim M \lesssim 10^6 M_\odot$. Their luminosity will turn out to be given by the single equation $L \approx 0.1\, c^2\, dM/dt$, while their spectra can be highly diversified.

2. INTENSITY OF THE ACCRETION AND FLOW REGIMES

Let us imagine a massive object moving at a velocity u through a gas possessing no angular momentum. On the "back" side of such an object a conically shaped shock wave will be formed in which the gas will lose the component of its velocity perpendicular to the shock front. After compression in the shock wave, particles having sufficiently small impact parameters will fall into the star [1]. One can show that the infall of gas will begin at the characteristic distance

$$r_c = \alpha GM/v_c^2 = \alpha 10^{14} M v_{c(10)}^{-2}\ \mathrm{cm}, \qquad (1)$$

the distance at which the potential energy of the particles becomes comparable to the kinetic energy; and the flux of mass at the star will be

$$\frac{dM}{dt} = \beta 10^{11} M^2 v_{c(10)}^{-3} n_c\ \mathrm{g/sec}. \qquad (2)$$

In Eqs. (1) and (2) the mass M is expressed in solar masses, the velocity $v_c = (u^2 + a_c^2)^{1/2}$ is expressed in units of 10 km/sec, and the sound velocity a_c in the gas and the density n_c [atoms/cm^3] of the material drawn in refer to distances $r > r_c$. The dimensionless coefficients α and β are functions of the adiabatic index of the gas and the ratio u/a. We may take the rough approximations $\alpha \approx 1$, $\beta \approx 1$. Numerical values for various γ and u/a have been given by Salpeter [9]. Historically, Eq. (2) was first obtained by Hoyle, Lyttleton, and Bondi [11-13].

Note that for any reasonable value of the adiabatic index γ the diameter of the tail will be $d \approx r_c \gg r_g$, and the pressure will be finite. It therefore seems to us beyond doubt that a symmetrization of the flow should take place during infall, so that for $r \ll r_c$ the motion of the plasma may be considered radial (see Fig. 1).

In the spherically symmetric case, with back pressure absent, a supersonic flow of the gas will be established at $r \ll r_c$, that is, practically free fall [1]. To find the temperature variation, we shall write the second law of thermodynamics, $dE = -p\,dV + dQ$, in the form

$$\frac{3}{2} R^* \frac{dT}{dt} = R^* \frac{T}{\rho}\frac{d\rho}{dt} - 5\cdot 10^{20} T^{1/2} \rho \varkappa + \frac{dQ'}{dt}. \qquad (3)$$

Here R^* is the gas constant; the second term on the right-hand side describes the losses of 1 g of plasma to radiation ($\varkappa = 1$ corresponds to bremsstrahlung from a fully ionized plasma), and the third term represents the energy variation due to other nonadiabatic processes. Since $\rho \propto r^{-3/2}$, we have

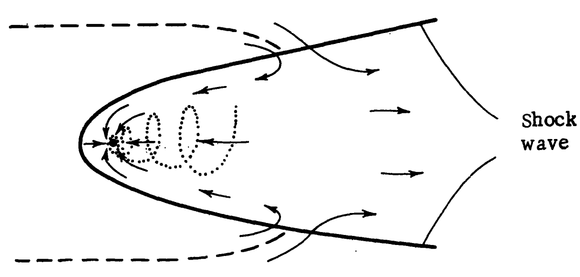

Fig. 1. The pattern of hydrodynamic accretion in the case where the star's own velocity u is much greater than the sound velocity a in the gas. The dashed curves correspond to the critical impact parameter. The dotted curve denotes the trajectory (helical) that the particles describe if an angular momentum relative to the star is present. In the figure the momentum vector is oriented parallel to the direction of motion of the object.

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$$\frac{dT}{dr}=-\frac{T}{r}+[2\cdot10^{-4}Mv_{c(10)}^{-3/2}n_c]\frac{\sqrt{T}}{r}\varkappa+\frac{dQ'/dt}{v\cdot\frac{3}{2}R^*}. \quad (4)$$

As it falls in toward a massive object the gas will be efficiently cooled through radiation ($T = [A \ln (r/r_0) + T_0^{1/2}]^2$); when $T \approx 5000°K$ is reached, recombination will begin and a temperature $T \approx$ const will be established. In the case of infall to an object of low mass, radiation will play a minor role; if the last term is neglected, the temperature variation will approach a $T \propto r^{-1}$ law, and the adiabatic index of the gas $\gamma \to 5/3$. The physical explanation of this difference is clear: the smaller the object, the smaller its gravitational radius, that is, its characteristic scale and the time for infall, and the radiation processes will become slow compared to the contraction process. Taking $dQ'/dt = 0$ (see the Appendix), we obtain for the critical mass, by Eq. (4),

$$M_{\mathrm{cr}}\sim 10^4M_\odot[T'_{(4)}]^{1/2}v_{c(10)}^{3}n_c^{-1}\varkappa_{(2)}^{-1}. \quad (5)$$

Here $T'_{(4)}$ denotes the temperature at the distance of interest to us in units of 10^4°K, and $\varkappa_{(2)} \equiv \varkappa/100$.

3. THE GAS-DYNAMICS APPROXIMATION

The high temperatures developed during infall toward a mass $M < M_{cr}$ cast some doubt on the applicability of the gas-dynamical approach. At $r < r_c$, the mean free path with respect to Coulomb collisions,

$$l=kT^2/ne^4\cdot L_{\mathrm{Coul}}\approx 10^{12}T_{(4)}n^{-1}\,\mathrm{cm}, \quad (6)$$

will in this case far exceed the characteristic size r of the region. For $M \approx M_\odot$, the free path $l \approx r$ even at the critical radius. We recall that the mass flux at the star in the approximation of noninteracting particles is smaller than the gas-dynamical flux (2) by a factor $(c/a_{\mathrm{sound}})^2 \approx 10^9$ [1].

However, the material drawn in will contain magnetic fields. The Larmor radius of protons moving at thermal velocities will be smaller than the dimensions of the region of motion even at field strengths $H > 1.3\, T^{1/2}\, r^{-1}$ gauss. Inasmuch as $T \leq T_c\,(r_c/r)$, we have the condition for capture

$$H(r)\gg 10^{-12}T_{c(4)}^{3/2}M^{-1}(r_c/r)^{5/2}\,\mathrm{gauss}. \quad (7)$$

The field at infinity is of order 10^{-6} gauss, so that in order for the condition (7) to be satisfied out to $r = r_g$ it is necessary that H increase with depth at least as $r^{-0.8}$. We shall see in Sec. 5 that there are grounds for expecting a far steeper rise in H(r), so that the gas-dynamics approach would be applicable.

The rise in the magnetic field would prevent any heat exchange between the different layers (see the Appendix). It would also affect the radiation and motion of the plasma. But first let us digress to consider one other topic.

4. LUMINOSITY AND EFFICIENCY IN THE IDEALIZED PROBLEM

For $M > M_{cr}$ the gas will be practically isothermal, so that the luminosity

$$L=\frac{dM}{dt}R^*\int_{r_1}^{r_2}T\frac{dn}{n}\approx 10^{34}M_{(5)}^2v_{c(10)}^{-3}n_c\ \mathrm{erg/sec}. \quad (8)$$

Here $M_{(5)} \equiv M/10^5 M_\odot$, $T \approx 5000°K$, and r_1 is the radius below which radiation will rapidly be quenched by general-relativity effects (gravitational plus the Doppler red shift) [1]. Roughly speaking, $r_1 \approx 2r_g$. The luminosity (8) will fall mainly in the optical range and will result from line and recombination emission. If $M < M_{cr}$, the plasma temperature will increase inward along an adiabatic curve, and the luminosity of the spherical layer bounded by r and r/2 will be

$$L(r)\approx r^3\varkappa 10^{-27}\cdot n^2\cdot T^{1/2}(r)$$
$$\approx 10^{21}M^3v_{c(10)}^{-6}n_c^2[T_{12}(r)]^{1/2}\ \mathrm{erg/sec}. \quad (9)$$

The value $T(r) \approx 10^{12}$ °K may be regarded as an upper limit. The optical depth

$$\tau(r)=\int_r^{r_c}\sigma n_c(r_c/r)^{3/2}dr\approx 10^{-6}(\sigma/\sigma_k)M(r_g/r)^{1/2}n_cT_{c(4)}^{-3/2} \quad (10)$$

(where σ_k is the Compton cross section) will always be much less than unity if $M < M_{cr}$, but if $M > M_{cr}$ the interior regions may become opaque, despite the Doppler shift.

In the approximation considered here, the efficiency of black holes would be extremely low. If accretion by an object with $M > M_{cr}$ takes place, only $\approx 10^{-8}$ of the mass of the infalling material will be converted into radiation; if $M < M_{cr}$ the efficiency will be even lower. The actual situation, however, is more favorable than this idealized one.

5. THE INFLUENCE OF MAGNETIC FIELDS[1]

Any plasma that is drawn in will necessarily contain magnetic fields. The observable effects will depend in an essential way on the law for the growth of the fields during the infall process. In our opinion there is only one real possibility: the

[1] See the note added in proof.

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magnetic energy ε_m and the gravitational energy ε_{gr} per unit volume should be of the same order not only at the critical radius (where all four energies – gravitational, kinetic, thermal, and magnetic – would be of the same order) but also in the zone $r < r_c$. We can prove this statement by assuming the contrary. For suppose that in some region $\varepsilon_m \ll \varepsilon_{gr}$; then the field would not affect the infall, and because of strict freezing-in (it is readily seen that during infall the magnetic viscosity will always be far smaller than the kinematic viscosity) its radial component H_r would increase according to the law $H_r \propto r^{-2}$, so that $\varepsilon_m = H^2/8\pi \propto r^{-4}$. However, $\varepsilon_{gr} \propto r^{-5/2}$, and an equality $\varepsilon_m \approx \varepsilon_{gr}$ would therefore be established very rapidly. On the other hand, the inequality $\varepsilon_m \gg \varepsilon_{gr}$ also would not be possible, because the field energy (due to freezing-in) would be derived from the energy of contraction, that is, from the kinetic energy, which would be smaller than ε_{gr}. We are therefore left with the condition $\varepsilon_m \approx \varepsilon_{gr}$. The behavior of the infall will be highly complicated in this situation: the field will have a predominantly radial character, and will be annihilated at the boundaries of sectors in which it is oppositely directed; the plasma will be inhomogeneous; the rate of infall will be nonuniform; very strong gutter instabilities will develop periodically in regions where $H \perp r$; and so on.

We shall nevertheless assume that despite the magnetic field, on the average the infall of gas does not depart seriously from free fall; that is, we shall suppose that $\bar{v} \approx (2GM/r)^{1/2}$ and $\bar{n} \propto r^{-3/2}$. Admittedly, both our idealizations may seem far-reaching, but it is natural to make them in our first steps toward a solution of the problem. We shall, then, let $H^2/8\pi = anGMm_p/r$, with $a \approx 1$.

In the case of infall toward a mass $M < M_{cr} \approx 10^4 M_\odot$, the plasma will be strongly heated, and the synchrotron losses will rapidly become decisive. In the range $T > 10^{10}$ °K, Eq. (4) will take the form ($dQ'/dt = 0$)

$$\frac{dT}{dr} = -\frac{T}{r} + [3 \cdot 10^{-8} M^2 v_{c(10)}^{-3/2} n_c] \frac{T^2}{r^2} a. \qquad (11)$$

Its solution is $T = (Cr + A/2r)^{-1}$; after the value

$$T_{\max} = 3 \cdot 10^{12} M^{-1/2} v_{c(10)}^{3/4} n_c^{-1/2} a^{-1/2} \, {}^\circ\mathrm{K} \qquad (12)$$

is reached the "temperature" will begin to fall. The efficiency of radiant energy release will be

$$\eta = 0.2\, mc^2 T_{\max(12.5)}, \quad \text{if} \quad T_{\max} < 3 \cdot 10^{12}, \qquad (13a)$$

$$\eta = 0.2 mc^2 T_{\max(12.5)}^{-3}, \quad \text{if} \quad T_{\max} > 3 \cdot 10^{12}. \qquad (13b)$$

Of course, since equilibrium will not have been established during the accretion process [see Eq. (6)], the "temperature" T should be interpreted not as the Maxwellian parameter but as the mean energy of motion of the electrons across the magnetic field. Equations (11-13) as well as (17-19) below are, to some extent, merely illustrative in character. (In a separate paper [17] we have given a more detailed discussion of the circumstances of magnetic accretion, a theorem regarding the "equipartition of energy," and a demonstration that in the case of accretion by "black holes" the synchrotron mechanism should convert about $0.1\ mc^2$ of the infalling material into radiation.) We shall defer to Sec. 8 a description of the corresponding spectrum; we first wish to point out one possible factor that might raise the efficiency.

6. THE INFLUENCE OF ANGULAR MOMENTUM

Interstellar gas, generally speaking, would possess a certain angular momentum K relative to the line of motion of a hole. It is well recognized [1] that, in general relativity, particle capture is possible if $K < K_g = 2mcr_g$. After it approaches a gravitating center an isolated particle with $K > K_g$ will again recede to infinity. According to Sec. 3, however, plasma at any distance from a collapsed object may be regarded as a continuous medium. Its compression at the tail of the flow, in the shock wave, will be accompanied by radiant energy release; if this energy becomes negative, then matter can never leave the neighborhood of the hole. The corresponding criterion is evident: it is necessary that the momentum K be much smaller than the quantity $K_c = mr_c v_c$. Thus if the momentum of the material drawn in satisfied the inequality

$$2mr_g c < K \ll mr_c v_c, \qquad (14)$$

then before they fall into the hole the particles will go into a stationary orbit. The minimum radius of a stable stationary orbit would be $r_{min} = 3r_c$ [18]. In order for a particle in Keplerian motion to reach r_{min}, it should emit radiation of $0.07\ mc^2$; if the role of viscosity is appreciable and nearly solid-body rotation prevails, the efficiency would be twice as great.

Might we expect the condition (14) to be satisfied under actual conditions? Denoting the tangential velocity component by v_t, let us write the inequality in the form

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$$1.2\cdot10^{-4}v_{c(10)}^{2} < v_{t(10)}(r=r_c) \ll v_{c(10)}. \qquad (14a)$$

First let us consider the left-hand inequality. Estimates indicate that the internal scale of interstellar turbulence, $l_0 = \mathrm{Re}_0\,\nu'/v_t$, will always be less than or of the order of the radius r_c (Re_0 is the critical Reynolds number, and ν' is the magnetic viscosity). Hence $v_t(r_c) = v_t(L_t)\cdot(r_c/L_t)^x$, where $L_t \approx 100$ pc and $v_t(L_t) \approx 10$ km/sec [19]. In the interstellar medium, because of suppression of turbulence by the magnetic field and the formation of shock waves, the spectrum $v(l)$ should be steeper than a Kolmogorov spectrum ($x = 1/3$); evidently $1/2 \lessapprox x < 1$ [19, 20]. Let $x \equiv 2/(3+y)$. It is then easily seen than the first of the inequalities (14) will be satisfied for masses

$$M > M_t^{I} \approx 3.5M_\odot v_{c(10)}^{5}[1.2\cdot10^{-2}v_{c(10)}]^{y}. \qquad (15)$$

Thus for objects with stellar masses, spherically symmetric accretion will evidently be realized in many cases, while in some cases the plasma will be halted not far from r_g.

In the case of accretion of gas by very massive objects, rotation will undoubtedly play a role, and the radiant efficiency $\eta \approx 0.1\,mc^2$. It is now appropriate to inquire as to the influence of the momentum on dM/dt, that is, the right-hand inequality (14). For $L_t = 100$ pc and $v_t(L_t) = 10$ km/sec this inequality will become

$$\dot M \ll M_t^{II} \simeq 3\cdot10^{6}M_\odot v_{c(10)}^{2}. \qquad (16a)$$

The criterion (16a) refers to the case where $v_c \approx v_t \approx 10$ km/sec;[2] if $v_c \gg 10$ km/sec, only differential galactic rotation would be capable of preventing accretion. For a body 10 kpc away from the galactic center we would have in place of the criterion (16a):

$$M \ll M_t^{II} \simeq 3\cdot10^{9}M_\odot v_{c(50)}^{3}. \qquad (16b)$$

The role of the momentum of the gas in accretion by objects with $M > 10^6 M_\odot$ has been pointed out qualitatively by Salpeter [9]. He has also indicated a fundamental mechanism for momentum loss: the gas in adjacent turbulence cells would have opposite directions of rotation. We shall return to this topic presently, but we first with to call the reader's attention to an important case in which the sign of the momentum might not change.

7. ACCRETION IN BINARY SYSTEMS

Our motive in discussing this situation is clear: in addition to a high efficiency, binary systems would ensure an enormous loss rate dM/dt. Thus, variables of the β Lyrae type lose as much as 10^{-5} $M_\odot$/yr; under favorable conditions about one-half of this mass could fall into the second component. Hence the luminosity of holes in binary systems would in principle be capable of reaching 10^{38}–10^{39} erg/sec.

Around the dense component gas streams should form a disk with an approximately Keplerian velocity distribution. The mechanism for momentum loss would be viscosity, which would tend to produce solid-body rotation. The inner regions of the disk would be retarded, and the outer regions accelerated. Some of the gas would leave the binary system, while the rest would sink in toward the dense component. Very high temperatures would evidently be attained during this settling process (see the model calculation by Prendergast and Burbidge [22]).

Accretion by holes, neutron stars, and white dwarfs in close binary systems has been proposed on several occations [8, 22-24] as a source of energy. An important question arises here: would it be possible to distinguish accretion by a hole from accretion by a star? The answer will be clear from the considerations above. In the first case the radiation would all come from a hot, thin disk; in the second case half the radiation would be due to the disk and half to emission from the surface of the star, in which an appreciable contribution should be present from equilibrium radiation [25] and/or plasma oscillations [26]. Furthermore, in the case of accretion by a neutron star the radiation ought to contain a strictly periodic term (with $p \approx 1$ sec) arising from the rotation of the star. In the case of accretion by a hole, only random luminosity variations would be expected, with $\Delta t \approx 10^{-5}$–10^{-2} sec (see Sec. 9 below). Also, the emission spectrum of the disk itself probably would, in general, be quite flat. Thus a search for a hole in a binary system, based on the absence of an optically visible component [2-4], might actually exclude some of the objects sought.

8. GAMMA-RAY, X-RAY, AND OPTICAL STARS?

We shall now subdivide accretion into spherical, helical, and disk types, depending on the character of particle motion. The first two types would be realized around isolated objects; the last type, in binary systems. In the case of disk accretion, most of the energy should be released in the form of x-ray photons. Helical accretion would lead

[2] Note that under the conditions prevailing in the Galaxy, supermassive objects necessarily would rapidly diminish their velocity u [but not $v = (u^2 + a^2_{\mathrm{sound}})^{1/2}$] to about 10 km/sec [21].

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to the appearance of γ-ray stars as well as x-ray stars. Indeed, as we have been in Sec. 6, the spectrum of interstellar turbulence is such that in many instances the plasma would be halted (transferred from a helical to a circular orbit) in the vicinity of r_g. When a hole moves into the adjacent turbulence cell, where the gas is rotating in the opposite direction, particle collisions will begin to take place near r_g, and unlike the case of settling onto a disk, the process of momentum loss would here be very rapid.

It is worth noting that in the case of accretion by an isolated neutron star the role of the momentum of the gas would probably be small because of the small value of r_c (see Sec. 6). On the other hand, even if a disk were to develop, it would be located near the surface of the neutron star and would rapidly sink into the star. The integrated luminosity of the objects in this situation would be very low, of order 10^{30} ergs/sec [see Eq. (2)]; and most of the radiation would fall in the ultraviolet [27]. If the neutron star has a magnetic field, the infall of gas would be stopped, in general, far beyond r_g, and would be accompanied by Langmuir oscillations at radio frequencies [26].[3] Evidently, then, only "black holes" could be "pure" γ-stars.

In this connection it is interesting to note the recent discovery [28] of a discrete source of γ rays ($E_\gamma > 50$ MeV) which has not yet been identified with an x-ray object. Yet, the sensitivity of the x-ray equipment was one or two orders higher than the sensitivity of the γ-ray counters.

The intensity of disk-type accretion should remain unchanged over tens of thousands of years, apart from fluctuations associated with the inhomogeneity of the gas flow. (Possible eclipses of the disk by the normal component would be of special interest.) The radiation of isolated objects due to spiral-type accretion would undoubtedly exhibit a flare behavior. The minimum characteristic time for a flare would be of order r_c/v_c, that is, a few months. Curiously enough, among the known sources of hard x rays there are definitely two classes of objects: those whole luminosity has remained constant, on the average, throughout the entire period of observation (for example, Sco X-1 and Cyg X-2); and those whose luminosity has varied by tens of times within a year, either appearing or disappearing from the field of view (such as Cen X-2 and Cen X-4 [29, 30]). Observers have often suggested that Sco X-1 and Cyg X-2 might belong to binary systems [31-34].

The accretion of gas by an isolated hole of mass $M \approx 1$-$100\ M_\odot$ should, as mentioned in previous sections, be primarily spherical. Magnetic fields should play a definite role in the radiation. According to Eqs. (2) and (13a), the corresponding luminosity should be

$$L \sim 0.1 T_{\max(12.3)} c^2 dM/dt \approx 2\cdot 10^{33} M_{100}^{3/2} v_{10}^{-9/4} n^{1/2} a^{-1/2} \text{ erg/sec}; \quad (17)$$

here $M_{100} = M/100\ M_\odot$. The spectrum of the radiation should have a distinctive form: the intensity should remain nearly constant over a wide frequency range near

$$\nu_{\max} \sim 10^{14}\cdot M_{100}^{-3/8} v_{10}^{-9/16} n^{-9/8} a^{-13/8} \text{ Hz}, \quad (18)$$

an exponential decline should set in at $\nu \gg \nu_{max}$, and at $\nu \ll \nu_{max}$ there should be an extremely slow decline to frequencies at which absorption of the radiation becomes appreciable.

$$L(\nu) = \int_{\nu/2}^{\nu} (dL/d\nu)\, d\nu \propto \nu^{4/13}, \quad dL/d\nu \propto \nu^{-9/13}, \quad (19)$$

Coherent mechanisms and negative self-absorption might be operative.

In cases where γ rays are generated, they would be in addition to synchrotron radiation. However, because of the "accumulation" of material in circular orbits, the "peak" γ-ray luminosity should be one or two orders higher than given by Eq. (17).

The radiation of a "black hole" would of course heat the gas at $r > r_c$, thereby influencing the intensity of the accretion [see Eq. (2)]. One can show that for most cases of interest this effect would be insignificant, but in certain cases it could be decisive. A more thorough discussion of this topic, together with a solution of the self-consistent problem as exemplified by a neutron star, has been given elsewhere [27].

Conceivably, then, individual "black holes" might already be observable today, as faint optical stars with no lines but with a nonthermal spectrum extending far into the low-frequency range (as far as radio frequencies). Perhaps some of the objects heretofore regarded as type DC white dwarfs are actually "black holes."

9. A CRITICAL EXPERIMENT

What properties of the radiation would allow "black holes" of stellar mass to be distinguished reliably from other objects? In our view, such properties would be the exceptionally small size

[3]From the observational standpoint such objects might appear as "second generation" pulsars. Further details have been given elsewhere [26].

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of a hole together with the absence of any rotation. in other words, because of the development of instability in a magnetized plasma the luminosity of a hole would fluctuate on a time scale $\Delta t \approx 10^{-5}$-10^{-2} sec, but a periodic term should be entirely absent.

10. QUASAR-LIKE STARS?

Equations (5) and (16) imply that in the case of accretion by a hole with $M \approx 10^5 M_\odot$ the infalling gas will be cooled up to the onset of the "spiral" mode (somewhere in the zone $r \approx 10^{-4}$-10^{-3} r_c); $T \approx 5000°K$. The corresponding luminosities are given by Eq. (8), and are small compared to the integrated luminosity, but nevertheless they fall wholly in the optical range. The spectrum of the radiation – broadened emission lines, well-developed recombination bands, the presence of a nonthermal continuum and absorption lines – should to a large extent resemble the optical spectrum of quasars. On the other hand, holes with masses of order $10^5 M_\odot$ are interesting in that they might have come from "first generation" stars that developed from entropy perturbations in the pregalactic medium [35] (the remainder of these perturbations would presumably have served as the origin of the globular clusters [36]).

In the case of accretion by "superholes" with $M \gg 10^5 M_\odot$, the momentum of the gas would be expected to play a role from the very outset; but here too it would seem that in many cases a regime of "cold accretion" would develop, accompanied by a spectrum similar to that observed for quasars. We intend to examine this possibility in a separate paper.

APPENDIX

THE ABSENCE OF HEAT CONDUCTIVITY BETWEEN DIFFERENT LAYERS

Why have we consistently neglected the term dQ'/dt, representing the heat conductivity? For radiative conductivity, we have done so because the optical depth of the plasma is negligible [see Eq. (10)]; for ion conductivity, because the infall of the gas is supersonic; and finally, for electron conductivity, because the magnetic fields grow rapidly during the infall process. Let us consider this last point more carefully. According to Eq. (6), the time required for exchange of energy between different electrons will far exceed the time required for infall toward the hole. Thus heat conductivity could only arise from the migration of electrons. However, such migration will be severely limited by the small Larmor radius of the electrons ($l_L/r < 10^{-6}$), by the strictness with which the freezing-in conduction is satisfied, and by the tangling of the lines of force during infall (see Sec. 5). In the interior, where the temperatures and fields are large, there will in addition be a small "mean free path" relative to synchrotron losses, as compared to the characteristic scale of the motion.

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NOTE ADDED IN PROOF

Kardashev [37] was the first to point out the circumstance that in accretion by a "black hole" a substantial fraction of the rest mass of the infalling material might be liberated because of the presence of a magnetic field; in this connection see also the remark on page 360 of the Russian edition of Zel'dovich and Novikov's book [1]. The synchrotron radiation emitted upon accretion by the magnetosphere of a neutron star has been considered in recent papers [14,15]. Bisnovatyi-Kogan and Syunyaev, in discussing the problem of infrared sources [16], consider that in accretion by collapsed stars the annihilation of the magnetic field may lead to the formation near r_g of a shock wave at whose front a substantial part of the energy will be transformed into plasma oscillations with the emission of radiation. Our views concerning magnetic accretion have been set forth more fully in a separate paper [17].

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