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Accretion radiation from nearby isolated black holes

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Summary. Recent work attempting to establish the presence of dark matter in the solar neighbourhood has led to renewed interest in the search for the nature of this matter. Bahcall *et al.* attempt to exclude large ($\geq 2\,M_\odot$) objects by considering their tidal effect on wide binaries. Here we provide independent constraints on such dark massive objects, if they are black holes, by the requirement that their radiation due to accretion from the ISM should not make the nearest ones directly observable as optical objects. We also predict the expected infrared brightness. Ipser & Price have studied the observability of very massive ($10^5\,M_\odot$) pregalactic black holes in our galactic halo. Their more recent accretion model calculations allow such constraints to be evaluated for lower mass holes.

We show that halo holes must be less massive than about $10^3\,M_\odot$, and that the dark matter in the galactic disc cannot be made up of black holes of mass more than $10\,M_\odot$. Even if black holes do not make up the dark matter, they are expected to be present in the disc as remnants of massive stars. The failure to detect such holes so far is not in conflict with their presence provided the minimum mass $M_{\rm BH}$ of their progenitors is more than $10\,M_\odot$. More detailed analysis and improved observations could set more useful constraints on $M_{\rm BH}$, and if the holes do indeed exist some of them should be bright enough to be discovered and observed.

1 Introduction

We investigate accretion radiation limits for three different possible populations of holes. First, we consider the scenario studied by Ipser & Price (1977), in which the galaxy has a massive halo made of black holes which are the remnants of massive pregalactic stars. Carr, Bond & Arnett (1984) study the cosmological consequences of such massive pregalactic stars in detail. Lacey (1984) shows that such halo holes must have a mass of less than $10^6\,M_\odot$ to avoid heating up the galactic disc. These holes would traverse the disc of our galaxy rapidly (about $300\,\mathrm{km\,s^{-1}}$), and their luminosity would therefore be small unless the hole mass was at the upper end of the range. Secondly, we investigate the possibility that the local 'Oort limit' missing mass is made up of black holes, possibly stellar remnants of a first generation of galactic stars. According to Bahcall (1984) these objects must have a mean velocity of less than $100\,\mathrm{km\,s^{-1}}$ relative to the disc to be consistent with the dynamical data. We adopt this maximum value, which gives the lowest luminosity. Thirdly, we attempt to constrain stellar evolution theory by estimating whether the black hole remnants of ordinary massive stars in the disc should have been detected. Shapiro & Teukolsky (1983) calculate that there should be of order 10^8 holes of 10 solar masses left in the galactic disc from the ordinary stellar evolution of massive stars. They assume that all stars above $10\,M_\odot$ collapse into holes with no mass loss, so their calculations almost certainly lead to an overestimate of the density of such holes. We attempt to calculate a more probable estimate. In all cases, the limits from integrated background light (Carr 1979) are weaker and only exclude holes of larger mass than considered here. Hegyi, Kolb & Olive (1985, in preparation) also constrain the existence of black holes by both accretion and nucleosynthetic arguments.

2 Black hole accretion in the interstellar medium

The gas accretion rate depends on the relative velocities of holes and gas and on the gas density. For a hole moving with supersonic velocity u, the Bondi accretion rate is

$$\dot{M}=\pi\left(\frac{GM}{u^2}\right)^2 m_\mathrm{p} n u. \tag{1}$$

We adopt the accretion parameter $\bar{g}$ defined by Ipser & Price (1982), which in our notation is

$$\bar{g}=0.016\left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)\left(\frac{u}{100\,\mathrm{km\,s}^{-1}}\right)^{-3} \tag{2}$$

so that $\dot{M}\sim M^2\bar{g}$. The luminosity of the hole depends also on the efficiency ε with which the infalling mass-energy is converted into radiation. It is often suggested that while ε is as large as 0.1 for disc accretion, it should be very small for an isolated hole accreting spherically from the interstellar medium. However the work of Mészáros (1975) showed that if the dissipation of magnetic and turbulent energy is taken into account in the heating of the gas, high temperatures and quite respectable efficiencies are achieved. Ipser & Price (1982) performed detailed calculations which showed that for low accretion rates ε is also proportional to the accretion parameter $\bar{g}$ and the mass, reaching a maximum value of 0.01 for higher accretion rates. Since the brightness of a hole therefore depends on the square of the gas density, it is much easier to detect accreting holes in a clumpy interstellar medium. Accretion in the halo would be very weak indeed, and our calculations for halo holes are based on the radiation from holes accreting as they pass through the disc of the Galaxy near to the Sun. We emphasize that our results depend on the assumption that the spherical accretion flow is turbulent and dissipative; if it were smooth the Ipser–Price results would not be applicable and the luminous efficiencies would be much lower.

Recent work has somewhat clarified the nature of the interstellar medium in the solar neighbourhood. It is indeed clumpy, and locally very under-dense, with much of the volume within 50 pc of the Sun filled with hot thin gas that may be the result of recent supernova explosions (Paresce 1984). The ISM also contains a warm (10^4 K), thin ($0.1\,\mathrm{cm}^{-3}$) component together with many small cooler clouds. These clouds, detected by Knude (1979), have a mean density of $30\,\mathrm{cm}^{-3}$ and a size of 4 pc. Their filling factor is somewhat uncertain but is probably about 2 per cent, at least in the region beyond 50 pc. We will adopt these values, since most of our results depend on the ISM at a distance of about 50–100 pc, which is the regime studied by Knude.

There is also at least one denser nearby cloud of low optical depth, the Reigel–Crutcher H I cloud at about 125 pc in the direction of the galactic centre, with a density of $100\,\mathrm{cm}^{-3}$ (Crutcher & Lien 1984). At its eastern end it merges into the Aquila Rift molecular cloud. We estimate the H I cloud's volume to be at least $10^4\,\mathrm{pc}^3$.

If a Maxwellian distribution is assumed for the holes, with velocity dispersion v_0, then the fraction of them moving at speed less than v is $0.3(v/v_0)^3$, for $v \ll v_0$. Since the accretion rate also depends on the cube of the velocity, until the velocity drops to the sonic value below which the sound speed replaces u in equation (1), we obtain a limit for the nearest object better by a factor (v_0/v) by considering the small number of objects with sonic or subsonic velocity and thus maximum luminosity; the nearest such object will be brighter than the much closer but less luminous high-velocity objects. In practice, though, we must consider the whole range of velocities, as we are interested not in total luminosities but in the radiation in specific wavebands. Also, the above analysis assumes that the distance of the object is not large compared with the ISM scale height.

If the hole radiates away the infalling mass-energy with efficiency ε, its luminosity is

$$L = \varepsilon \dot{M} c^2$$

$$= 8\times 10^{21}\varepsilon\left(\frac{M}{M_\odot}\right)^2\left(\frac{u}{100\,\mathrm{km\,s^{-1}}}\right)^{-3}\left(\frac{n}{1\,\mathrm{cm^{-3}}}\right)\mathrm{W}. \tag{3}$$

We require that the luminosity be less than the Eddington luminosity,

$$L_{\mathrm{Edd}} = 4\pi c G M m_{\mathrm{p}}/\sigma_{\mathrm{T}}$$

$$= 1.3\times 10^{31}\left(\frac{M}{M_\odot}\right)\mathrm{W}. \tag{4}$$

at which the radiation would drive away the infalling matter. Since

$$L/L_{\mathrm{Edd}} = 6\times 10^{-10}\varepsilon\left(\frac{M}{M_\odot}\right)\left(\frac{n}{1\,\mathrm{cm^{-3}}}\right)\left(\frac{u}{100\,\mathrm{km\,s^{-1}}}\right)^{-3}, \tag{5}$$

the radiation is sub-Eddington for the range of parameters that we will consider.

Let us examine the assumption of spherical accretion. If the infalling gas has enough angular momentum, it will form an accretion disc. The turbulent velocity scales with turbulence length scale l as $v \sim l^q$, where $q = 1/3$ for a Kolmogorov spectrum but may lie in the range 0.5 to 1 for the ISM. Observations indicate (Kaplan & Pikel'ner 1970; Ipser & Price 1977) that

$$\omega = v/l = 3\times 10^{-15}(l/80\,\mathrm{pc})^{q-1}\,\mathrm{rad\,s^{-1}}. \tag{6}$$

In this case l is the Bondi radius $r_{\mathrm{B}} = 2GM/u^2$. Ipser & Price derive the criterion for a disc assuming $q = 3/4$:

$$u < 6\left(\frac{M}{M_\odot}\right)^{0.6}\mathrm{km\,s^{-1}}. \tag{7}$$

The limits we will consider in Sections 3 and 4 are all for holes with speeds above this admittedly rather uncertain value. However, we have also calculated disc accretion spectra adopting the standard accretion disc theory of Shakura & Sunyayev (1973) and Novikov & Thorne (1973). In these models the flux emerges in the unobserved far-ultraviolet for most of the models we consider, and the limits obtainable from the small flux emitted at optical and X-ray frequencies are comparable with the limits obtained below using spherical accretion models.

For black hole spherical accretion spectra we adopt the models calculated by Ipser & Price (1982). They present a grid of model spectra calculated for masses $\log(M/M_\odot) = 1$, 3, and 5, and accretion parameters $\log \bar{g} = -4$ to 2 in steps on one order of magnitude. These spectra, some of which are illustrated in Figs 1 and 2, are rather flat and peak in the far-infrared for low $\bar{g}$ and in the visible for high $\bar{g}$.

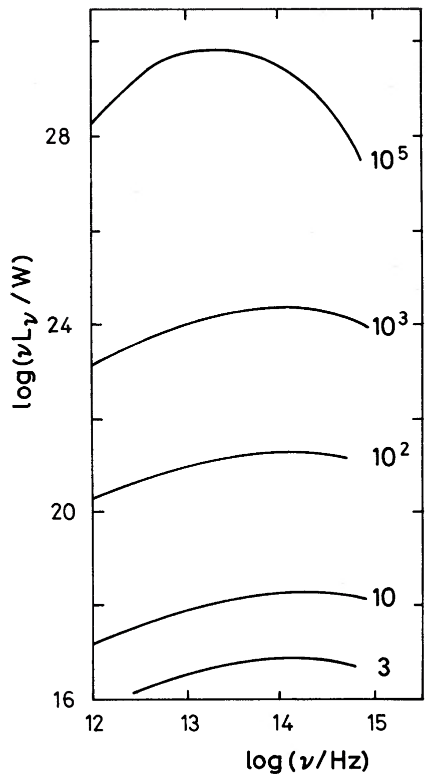

Figure 1. Synchrotron spectra from spherically accreting black holes with an accretion parameter of $\bar{g}=0.01$, based on Ipser & Price (1982). The curves are labelled by the hole mass.

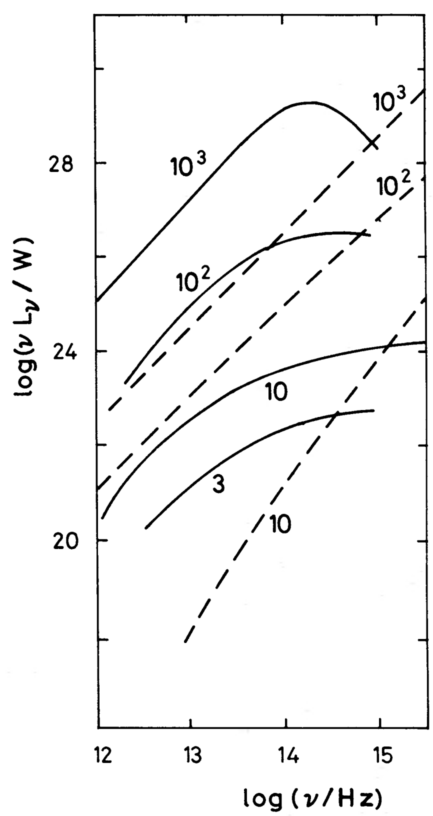

Figure 2. Synchrotron spectra from spherically accreting black holes with $\bar{g}=10$, based on Ipser & Price (1982). Dashed lines indicate disc accretion spectra for the same value of $\bar{g}$, which are comparable in flux with the spherical accretion spectra in the optical and turn over in the far-UV.

To assess the detectability of the brightest accreting holes, we estimate their apparent brightness in the *V* band (0.55 μm) and *IRAS* band 4 (100 μm). Brightnesses in the *K* (2.2 μm) and *IRAS* 12-μm bands have also been calculated. We perform the calculations for five masses: 3, 10, 10^2, 10^3 and $10^5 M_\odot$. Fig. 1 shows spectra adopted for different masses for the case $\bar{g}=10^{-2}$, corresponding to holes moving at 360 km s^{-1} in a cloud of density 30 cm^{-3}. Fig. 2 shows the spectra for holes moving at 36 km s^{-1}, or $\bar{g}=10$. Spectra for disc accreting holes, shown as dotted lines, are included for the high-mass cases for comparison.

The apparent brightness that such sources would have is discussed below for the three scenarios mentioned above. To use these predictions to set constraints is more difficult. It should be noted that the *IRAS* catalogue should contain all objects down to 1 Jy, and Luyten's proper motion surveys will contain almost all nearby objects with proper motion above 0.2 arcsec yr^{-1} down to visual magnitude 17 over about half the sky and to magnitude 14 over the whole sky (Luyten 1981). Whether such objects would have already attracted attention if they were toward the faint end of such surveys is unclear.

3 Black holes in the galactic halo

Suppose the galactic dark halo is composed of black holes with $v_0=300$ km s^{-1}, and mass density $10^{-2} M_\odot$ pc^{-3} locally (Bahcall & Soneira 1980). Then if the typical mass of such a hole is *M* solar masses, the nearest one will be at $r=3M^{1/3}$ pc. The nearest hole with a speed of v or less will on average be $1.5(v_0/v)$ times further away. The best limits, presented in Table 1, come from the nearest hole in a cloud or a more distant but slow one also in a cloud. The radiation from closer holes in the intercloud medium is always much smaller. For each mass, Table 1 shows the distance *r* of the nearest hole travelling at or below speed v, the corresponding *IRAS* band 4 flux, the *V* magnitude, and an estimate of the typical proper motion calculated from the speed and distance. The $V-K$ colours are mostly about +4, except for the $10^5 M_\odot$ case which has a predicted *K* magnitude of 3, clearly excluding this case. The 1000 $M_\odot$ holes with $V=15$ should have been

Table 1. Halo dark matter holes.

M	v(km/s)	r (pc)	V mag.	100 μ	μ ("/yr)
10^5	300	1000	10 *	400 Jy	
1000	300	100	15	.2 Jy	0.5
1000	100	1000	13	50 mJy	
100	300	50	20	1 mJy	
100	20	2000	14	0	
10	200	60	24	0	0.5

* K mag = 3.

Best limits on halo dark matter holes passing through clouds in the disk. The assumed velocity dispersion is 300 km/s; smaller values of v refer to the slowly moving Maxwellian tail of the distribution. The nearest sjch hole in a cloud is at a distance r and has an apparent V magnitude and IRAS band 4 flux as noted. μ is estimated typical proper motion.

picked up in the proper motion surveys, but 100 $M_\odot$ holes might have escaped detection – if the rare slowly travelling ones at $V=14$ exist, they would be easy to miss. We conclude that holes of mass above 1000 $M_\odot$ cannot constitute the suggested halo dark matter, thus improving the constraint set by Ipser & Price (1977).

4 The missing mass in the disc

The analyses by Bahcall (1984) of the dynamical evidence that 0.1 $M_\odot\,\mathrm{pc}^{-3}$ of dark matter is required to make up the Oort limit have renewed interest in the local missing mass. The claim by Bahcall, Hut & Tremaine (1984) to exclude dark objects of mass above 2 $M_\odot$ depends upon the existence of very wide binaries in the galaxy. Since the evidence for these objects rests on a rather small number of candidates, it is still interesting to exclude massive dark objects by independent constraints. Following Bahcall, we assume a velocity dispersion of 100 km s^{-1} for the objects, and also assume that a small fraction of the objects are moving slowly, as predicted by a Maxwellian velocity distribution.

The results are presented in Table 2, in the same format as Table 1. Holes of mass of or greater than 100 $M_\odot$ are clearly excluded, and more arguably the 10 $M_\odot$ case is also excluded, as it is unlikely that an unusual 12 mag object would have been overlooked. Even the low-velocity 3 $M_\odot$ holes are not far outside the proper motion survey limits, and a large proper motion survey to fainter magnitudes could pick them up. (The fast-moving limit, $V=20$ and $\mu=2.1$ arcsec yr^{-1}, should not be taken seriously because of the lack of nearby clouds.)

It is interesting to note the limits set by the RC H I cloud alone; for 100 $M_\odot$ there should be 10 objects, just in the proper motion survey, at $V=14$, and one of $V=11$. For 10 $M_\odot$, the cloud should contain 100 objects, all brighter than magnitude 20, with the brightest predicted to be magnitude 13; for 3 $M_\odot$ the predicted numbers are three times larger than this and the brightness 4 mag fainter.

Table 2. Disc dark matter holes.

M	v(km/s)	r(pc)	V mag.	100 μ	μ ("/yr)
10^5	100	300	5	10 Jy	0.1
1000	100	50	7	30 Jy	0.3
100	100	25	12	0.4 Jy	0.7
100	20	250	9	60 mJy	0.0
10	100	10	17	5 mJy	1.7
10	20	100	12	3 mJy	0.0
3	100	7	20	.3 mJy	2.4
3	20	60	15	.2 mJy	0.1

Best limits on disk dark matter holes in clouds, as for table 1. The assumed velocity dispersion is 100 km/s.

μ is an estimate of the likely proper motion of the brightest hole.

The cases with values of r less than 50 are suspect as clouds are thought to be underabundant in the immediate solar neighbourhood.

We conclude that if black holes make any significant contribution to the local missing mass, they must be of low mass ($<10\,M_\odot$), and even then their existence might be subject to observational confirmation, particularly by faint proper-motion surveys targeted on nearby H I clouds.

5 The Population I remnants

How many black holes do we expect in the solar neighbourhood as a result of late evolution of massive stars? Let us assume that all stars of initial mass M above some critical mass $M_{\rm BH}\gtrsim 10\,M_\odot$ end up as black holes of mass ϕM. For simplicity we will assume ϕ is independent of M; this reflects our lack of understanding of mass loss in massive stars. The number density of remnants of stars of mass M is

$$n(M)=n_*(M)\,\frac{t_0}{t_{\rm ms}}\,\frac{h_1}{h_2} \tag{8}$$

where n_* is the number density of presently shining stars, distributed with (young) scale height h_1, h_2 is the scale height of the old remnant population, and $(t_0/t_{\rm ms})$ is the ratio of the age of the galaxy to the lifetime of the stars. We also assume here that the star formation rate is roughly constant over the life of the galaxy. Using the initial mass function for massive stars derived by Miller & Scalo (1979), we find

$$N(M)\,dM=0.16M^{-3.3}\,dM\,({\rm pc}^{-3}) \tag{9}$$

for $M>10\,M_\odot$.

A crude fit to the V magnitude of a spherically accreting hole in this mass range, fitted to the Ipser & Price data, is

$$\begin{aligned} V&=-2.5\log[0.06(\phi M)^3 n^2 v^{-6} r^{-2}] \qquad v>4(Mn)^{1/3}\\ &=-2.5\log[0.22(\phi M)^2 n v^{-3} r^{-2}] \qquad v<4(Mn)^{1/3} \end{aligned} \tag{10}$$

where n, v, and r are gas density in cm^{-3}, hole velocity in km s^{-1} and hole distance in pc respectively. The break is due to the saturation of ε discussed in section 2. (At even lower velocities, equation (7) would imply that discs form, but despite their totally different luminosities and spectra the visual magnitudes calculated from the standard disc model are coincidentally within a magnitude of the spherical accretion models for the parameter range of interest; we therefore ignore the uncertain question of disc versus spherical accretion.)

With this approximation and assuming a Maxwellian distribution with the velocity dispersion of 30 km s^{-1} expected for such a population, and the interstellar cloud model used above, we can estimate the number density of objects above a given absolute magnitude by integrating the number moving slowly enough to be seen at a given mass over the mass distribution. We hence calculate the number of holes as a function of apparent visual magnitude in a given distance range, which we choose to be 50–150 pc to coincide with the range in which the clouds are known to exist (Knude 1979, 1983).

Shapiro & Teukolsky (1983) take $M_{\rm BH}=10\,M_\odot$ and $\phi=1$ and, using the Salpeter mass function get $n=8\times10^{-4}$ pc^{-3}. We take $\phi=0.3$ to make a more reasonable minimum remnant mass of $3\,M_\odot$, or just above the neutron star maximum mass, and we adopt the Miller–Scalo IMF. We calculate that the brightest hole in this case would be 11 mag. The integral over mass and distance is dominated by the contribution from slow-moving (20 km s^{-1}) low-mass, distant objects. The distribution of holes as a function of apparent magnitude is shown in Fig. 3 as model 'A'. For a more pessimistic model, we take $M_{\rm BH}=50\,M_\odot$, as suggested by empirical evidence presented by

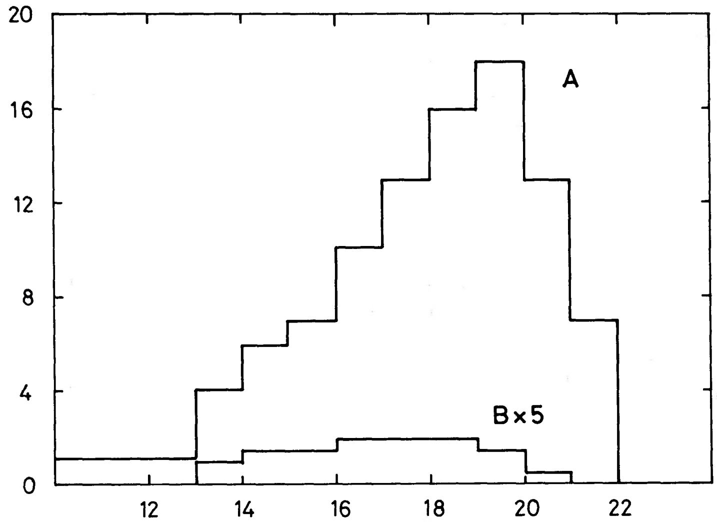

Figure 3. Predicted distribution of apparent magnitudes for black holes accreting spherically from clouds between 50 and 150 pc from the Sun, based on the distribution of masses and velocities described in the text. Assuming that the filling factor is 2 per cent, there are predicted to be 100 holes in clouds in the given distance range for model A, but only 2 for model B.

Schild & Maeder (1985), and $\phi=0.1$. This model is labelled 'B' in Fig. 3. In this case the brightest object would be only 16 mag. In this simple model the results are much more sensitive to the mass loss parameter ϕ than to $M_{\rm BH}$, and so an attempt to estimate the minimum allowed $M_{\rm BH}$ from this model would have little meaning, but it does seem that $M_{\rm BH}$ must be much larger than $10\,M_\odot$ to explain the fact that no accreting holes have been observed. Conversely, these calculations indicate that if $M_{\rm BH}$ is $50\,M_\odot$ or lower, it may eventually be possible to detect and observe unambiguously identifiable black holes. An isolated hole accreting from the ISM could be less ambiguous than the current binary star candidates, because the inner regions would be less obscured, and could provide a cleaner laboratory to study relativistic astrophysics.

The best hope for their detection is a study of high proper motion objects in the optical combined with improved mapping of the local ISM to locate nearby regions of high density. We cannot yet constrain stellar evolution theory by the non-observation of black holes, but the results presented here suggest that such a constraint is possible, and that if black holes are really a normal endpoint of massive star evolution, it should eventually be possible to discover them. If improved instrumentation fails to reveal any such objects, we may be forced to reassess our ideas about the ubiquity of black holes.

Acknowledgments

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