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SEARCHING FOR STELLAR MASS BLACK HOLES IN THE SOLAR NEIGHBORHOOD

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ABSTRACT

We propose a search strategy for isolated stellar mass black holes in the solar neighborhood using information from the Sloan Digital Sky Survey. Accretion of the interstellar medium onto an isolated black hole is expected to result in a blended, thermal synchrotron spectrum, roughly flat from the optical to the far-infrared. We find that the Sloan Survey will be sensitive to isolated black holes in the range 1–100 $M_\odot$ out to a few hundred parsecs. We find that multiband photometry can distinguish black holes from field stars, with black holes having colors similar to QSOs. The holes may then be isolated from QSOs because they have a featureless spectrum with no emission lines. The Sloan Survey will likely find hundreds of objects that meet these criteria, and to reduce the number of candidates we suggest other selection criteria such as infrared observations and proper-motion measurements. If no black hole candidates are found in this survey, important limits can be placed on the local density of black holes and the halo fraction in black holes.

Subject headings: accretion, accretion disks — black hole physics — dark matter — Galaxy: halo — Galaxy: solar neighborhood

Shvartsman (1971) first pointed out that a stellar mass black hole accreting matter from the interstellar medium (ISM) will have a flat, optical spectrum, with no lines, and irregular fluctuations. Because of the expected rarity and relatively weak luminosity of these objects, however, a dedicated, systematic search has not been performed. Nonetheless, Ipser & Price (1977) have placed limits on the halo population of large mass black holes ($M > 10^5\ M_\odot$) based on nondetection in infrared surveys, and McDowell (1985) has argued that proper-motion surveys have not revealed any obvious black hole candidates; from this he has placed important (though model-dependent) limits on both the halo population of black holes down to about $M = 10^3\ M_\odot$, and the disk population down to about $M = 10\ M_\odot$. Carr (1979) and Hegyi, Kolb, & Olive (1986) have also placed limits on black hole populations from their possible contribution to the X-ray background. Carr (1994) has also reviewed other limits placed on the density of black hole populations.

The planned Sloan Digital Sky Survey (SDSS), however, offers an excellent opportunity to search for isolated black holes in our solar neighborhood in a more systematic manner. In fact, through planned QSO searches, the SDSS will serendipitously collect both photometric and spectroscopic data on viable black hole candidates. Because ISM accretion on a black hole is a relatively simple problem in the optically thin limit, one can calculate the emergent spectrum and use it as a template to select candidates from the SDSS data. This systematic search can place much stronger limits on black hole populations if no candidates are found, especially when this survey is combined with proper-motion studies and infrared surveys that will help to isolate further the black hole candidates.

The first calculation of the emergent spectrum of a black hole spherically accreting in the ISM was by Shvartsman (1971), and since then numerous authors have investigated the problem in detail (e.g., Zeldovich & Novikov 1971; Novikov & Thorne 1973; Shapiro 1973; Ipser & Price 1982).[1] The bremsstrahlung luminosity was found to be very weak, but if interstellar magnetic fields are included in the accretion process, the magnetic field is drawn in and compressed to higher field strengths (about 10 tesla at the horizon for standard ISM conditions), and the resulting synchrotron luminosity can be quite high, with emission efficiencies as large as $0.01\ \dot{M}_c^2$.

We have calculated numerically the emergent spectrum following the method of Ipser & Price (1982). In Figure 1 we show predicted spectra for various ISM densities and black hole masses. We only consider black holes with mass $M \leq 100$ $M_\odot$ because the accretion rate for these "smaller" black holes is low enough that the accreting fluid will be optically thin for most ISM conditions. This is a reasonable mass range for a disk population, though halo holes may be more massive (Carr 1994). Because of the relative simplicity of this system, the calculation of the spectrum is fairly model independent, though there are still outstanding issues as to exactly how the magnetic, gravitational, kinetic, and thermal energies of the fluid are partitioned. Ipser & Price (1982) parameterize the amount of equipartitioning in each form of energy (e.g., kinetic, magnetic), and for a reasonable ranges of these parameters the spectrum is not dramatically affected.

In our calculations we have added the effect of the black hole moving with velocity V. The effect of motion is easily accounted for by making the substitution $a_\infty^2 \to a_\infty^2 + V^2$ (Bondi 1952). Note that $a_\infty \simeq (16.6\ \mathrm{km\ s^{-1}})(T_\infty/10^4\ \mathrm{K})^{1/2}$ is the sound speed in the ISM with temperature T_∞, where we have assumed that ISM is polytropic with $P \propto n^{5/3}$.

Thus the total synchrotron luminosity of the black hole is

$$L_{\mathrm{synch}} \approx 4.5 \times 10^{27}\ \mathrm{ergs\ s^{-1}}\,\beta_d\,\beta_V\left(\frac{M}{M_\odot}\right)^3 \times \left(\frac{\rho_\infty}{10^{-24}\ \mathrm{g\ cm^{-3}}}\right)^2\left[\left(\frac{V}{16.6\ \mathrm{km\ s^{-1}}}\right)^2 + \frac{T_\infty}{10^4\ \mathrm{K}}\right]^{-3}, \tag{1}$$

[1] For a recent review of black hole accretion see Chakrabarti (1996).

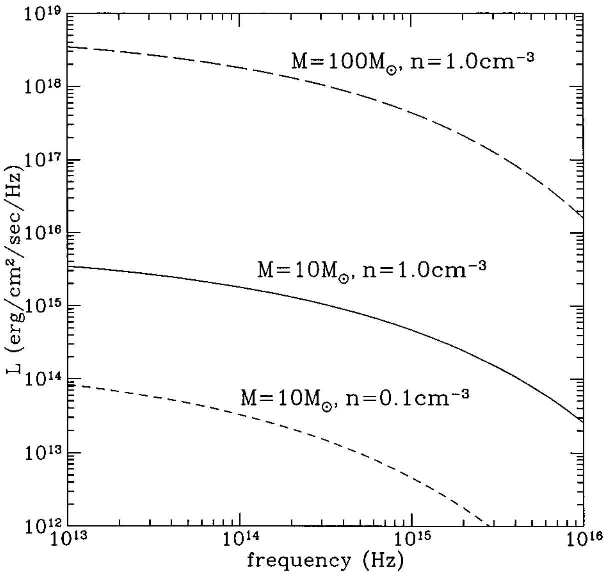

FIG. 1.—Emergent spectra of accreting black holes for various black hole masses and ISM densities.

where β_v and β_d are the equipartition parameters for bulk motion and dissipation discussed by Ipser & Price (1982). We set $\beta = 1$ unless otherwise stated. Equation (1) is valid for standard ISM conditions and for black holes of mass $M < 100$ $M_\odot$, where accretion rates are relatively small (Ipser & Price 1982). As pointed out by Shvartsman (1971), the spectrum is quite flat and falls off exponentially above a cutoff frequency of $\nu_{\rm cutoff} \approx 10^{15}$ Hz for standard ISM conditions, and $\nu_{\rm cutoff}$ is roughly independent of the black hole mass (see also Ipser & Price 1982). Note that equation (1) is valid for seed fields as low as 10^{-9} G.

We should note here that this calculation of the emergent spectrum assumes the ISM is fully ionized. Although as much as 70% of the local ISM may be ionized (Cox & Reynolds 1987), it is also true that in some regions it will be mostly neutral hydrogen. Strictly speaking, the ionization fraction will affect the accretion rate and the temperature profile of the accreting fluid, but because of energy equipartition near the Schwarzschild radius r_S, where most of the emission takes place, one might expect the temperature profiles to be similar near r_S in both the H I and H II cases. The only significant difference between the two cases may be in the total luminosity and not in the emergent spectrum. A more precise answer requires a calculation including neutral hydrogen.

Having discussed the emission spectrum, let us now consider a search strategy for black holes with the SDSS. The first step is to predict the apparent magnitude of the holes, taking into account their intrinsic luminosity and average expected distance. Shapiro & Teukolsky (1983) have estimated the number of stellar mass black holes in the Galaxy to be as much as 10^8. Assuming that the black holes are homogeneously distributed in a halo of 20 kpc, this translates to a local number density of 3×10^{-6} pc^{-3}, and possibly more if the black holes are concentrated in the disk. Therefore, on average one would expect to find at least a few stellar mass black holes out to a distance of about 100 pc. A similar calculation can be made by presuming that black holes comprise a significant fraction of the halo as discussed below.

Whether or not a black hole in our solar neighborhood will be observed depends on the ISM in which it is embedded. The general features of density and temperature of the local ISM are known (Cox & Reynolds 1987; Diamond, Jewell, & Ponman 1995). Unfortunately, we are in a hot, underdense local bubble of the ISM, and this significantly decreases the accretion rate, hence the luminosity, of the black holes. Perpendicular to the Galactic plane, the local bubble of very hot (10^5 K) and very rare (0.05 cm^{-3}) ISM is known to extend as much as 200 pc. Toward the Galactic center, however, the local bubble only extends out to a distance of about 60 pc. The local ISM is known to be inhomogeneous (Cox & Reynolds 1987); for example, the Sun is embedded in a slightly overdense region ($n \sim 0.1$ cm^{-3}, $T \approx 10^3$–10^4 K) known as the "local fluff," which extends about 20 pc. As seen from Table 1 and equation (1), the luminosity is a very sensitive function of ISM conditions.

TABLE 1

g MAGNITUDES OF BLACK HOLES AT 10 PARSECS

$M_{\rm BH}$ ($M_\odot$)	n = 1 cm^{-3}	n = 0.1 cm^{-3}	Local Bubble
1.............	22.05	26.89	37.02
10	14.55	19.39	29.52
100	7.38	11.89	22.02

NOTE.—Magnitudes are given for various black hole masses $M_{\rm BH}$ and ISM densities n. For the local bubble we set n = 0.05 cm^{-3} and $T_{\rm ISM} = 10^5$ K. Otherwise we set $T_{\rm ISM} = 10^4$ K, and for all cases $V = 0$. To find magnitudes at other distances, add 5 log (D/10 pc) to the values in the table. The SDSS magnitude limit is about $m \simeq 22$.

As shown in equation (1), the velocity of the black hole is also an important factor in determining the luminosity if the black hole has a relative velocity much greater than the sound speed velocity of the ISM. Consider two populations of black holes, one corotating with the disk and another forming a halo. Corotating black holes have average random velocity with respect to the disk of about 10 km s^{-1}. For ISM temperatures greater than 10^4 K, this velocity will not be important. However, for a halo population the average random velocity is about 270 km s^{-1}, which is so large that the luminosity is reduced by a factor of about 10^7 over the disk population case. As discussed later in this Letter, if we assume a Maxwellian velocity distribution, only a small fraction of halo black holes will have a relative velocity small enough to be sufficiently luminous.

Assuming that there are black holes bright enough to be observed by the SDSS, we must then determine how to distinguish them from the multitude of other sources such as field stars, galaxies, and QSOs. Fortunately this may not be a difficult task. To demonstrate this, we have calculated the photometric colors *ugriz* (as defined by the *AB* magnitude system used by the SDSS and detailed by Fukugita et al. 1996) of a sample of several black holes, and plotted them in Figure 2. The sample includes black holes ranging in mass from 3 to 100 $M_\odot$ embedded in the ISM with densities from 0.01 to 10 cm^{-3}. We also varied the equipartition parameter β_d from 0.25 to 0.9. Note that changing the temperature of the ISM has an effect similar to that of changing the ISM density. We have also plotted the colors of stars ($18.5 < m_r < 21.5$) and spectroscopically confirmed quasars taken from the data sample of Trèvese et al. (1994). The data have been transformed to SDSS colors (Newberg & Yanny 1995), and overall errors are about 0.1 mag. This color-color plot reveals that

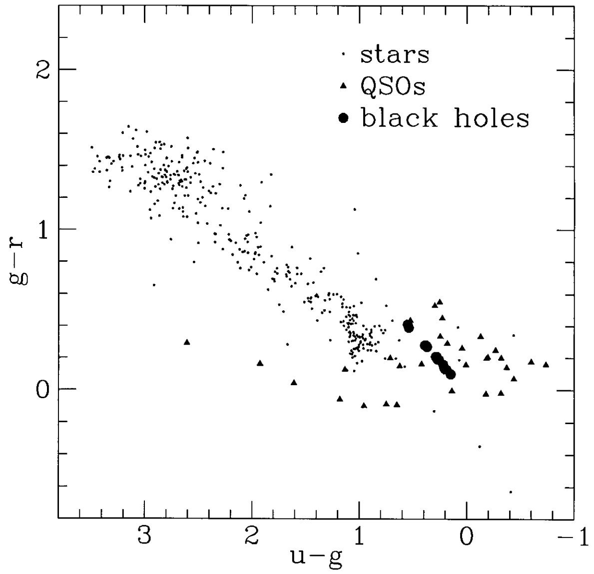

FIG. 2.—Color-color diagram for stars and QSOs, taken from Trèvese et al. (1994), and the expected colors of isolated black holes accreting the ISM. Notice that the black hole locus is distinct from the main-sequence stellar locus, and lies within the QSO locus. The SDSS QSO search will consider objects "bluer" (below and to the right) than the main-sequence stars to be QSO candidates.

black holes occupy only a small region of color space, and the black hole locus is easily distinguishable from that of main-sequence stars. In addition, black holes share the same region of color space as QSOs and will inadvertently be included as QSO candidates.

This is a fortuitous result for many reasons. The SDSS is expected to record about 10^8 objects, and the QSO search algorithm (Gunn 1995; Newberg & Yanny 1995) will cull this number down to about 10^5 QSO (and hence black hole) candidates. In order to find black hole candidates, one can utilize the fact that spectra will be taken of all QSO candidates. The spectra will be helpful for two reasons. First of all, black hole spectra will be featureless, so any spectrum with lines is not that of a black hole. Second, for a given black hole mass and ISM conditions, one can calculate the possible range of emergent spectra, and use these calculated spectra as a template for comparison with the measured spectra. Naturally, this is similar to saying that the spectra occupy a small region of color space.

Once one has found a candidate without emission lines and with a spectrum expected for a black hole, how can one be sure that it is not a star or some other object? For example, as pointed out by Shvartsman (1971), DC dwarfs may appear similar to accreting black holes. Photometrically, DC dwarfs appear as quasars, and their spectra have no features or show weak carbon features (Green, Schmidt, & Liebert 1986). Novikov & Thorne (1973) also point out that neutron stars with little or no magnetic field may also have spectra similar to those of black holes. However, most of the radiation is emitted near the "surface" of these objects where the boundary conditions are quite different, and thus it will probably not be difficult to distinguish between a black hole and a neutron star. In addition, recall that synchrotron emission is the dominant mechanism, with fields approaching 10 tesla (T). This is tiny compared even to "small" magnetic field neutron stars, keeping in mind that pulsars have magnetic fields of about 10^9 T.

There are several additional tests one can perform in order to be more confident that a candidate is a nearby accreting black hole. Perhaps the most detailed test will involve observations of the spectrum at longer wavelengths. As shown explicitly by Ipser & Price (1982), the spectrum is mostly flat and extends to a lower cutoff frequency $\nu_{\rm low} \approx 10^{12}$–$10^{13}$ Hz, depending on the black hole mass and ISM conditions. Below this frequency the spectrum goes as ν^2. This suggests that one may be able to search for the infrared signal of the black hole candidates with surveys such as the *IRAS* point source survey or with *ISO*. To give an example, for a 30 $M_\odot$ black hole in standard ISM conditions at a distance of 10 pc, $m_g \approx 12$ and the expected flux at 30 μm is of order 0.1 Jy, which is on the lower end of what is measurable by *IRAS*.

Besides the peculiar flat spectrum of the black hole, one can also test for variability in the luminosity and spectrum. Novikov & Thorne (1973) have estimated that plasma instabilities will result in luminosity variations on timescales of 10^{-4} to 10^{-2} s. In addition, they point out that there will be variability due to the black hole passing through different regions of the inhomogeneous ISM. They estimate the minimum timescales for this variability to be

$$\Delta t > 2b_{\rm capture}/V \approx 10 \text{ yr} \left(\frac{M}{M_\odot}\right)\left(\frac{V}{10 \text{ km s}^{-1}}\right)^{-3} . \qquad (2)$$

Interestingly enough, for halo black holes with $V \sim 270$ km s^{-1}, the variability is on the order of *days*, and naturally the variability is not expected to be periodic.

As pointed out by McDowell (1985), since the black holes are so close, another important test is to measure their proper motion and distance, which may be determined by parallax. Even if the black hole is farther than 100 pc away and has a tangential velocity of 10 km s^{-1}, one should be able to measure the proper motion over the span of a few years. Of course, one may also rule out candidates with velocity and distance measurements that are not in accordance with an expected luminosity, calculated using equation (1) and reasonable ISM conditions and black hole mass range.

One important question is how many objects one should expect to be selected as black hole candidates in the Sloan Survey. We estimate this by noting that in the Palomar-Green catalog of ultraviolet-excess stellar objects (Green et al. 1986), about 0.3% of the objects are unknown, that is, they have no identified spectral features. If we assume that the SDSS will see approximately 10^5 UV-excess objects, then we roughly estimate that one will find about 300 unknown UV-excess objects. Since accreting black holes have no spectral features, then we identify these unknown objects as black holes.

Finally, let us make one more important point. Because of the relatively high luminosity of black holes with mass $M > 10$ $M_\odot$, there are important consequences if no black holes are found in the Sloan Survey. To illustrate this, let us determine the maximum amount black holes can contribute to the dark matter halo if they are not detected in the SDSS. The number of black holes observable by the SDSS is

$$N_{\rm obs} = n_{\rm BH}\left(\frac{M_\odot}{M}\right)\Omega\left(\frac{d^3_{\rm max}(M, \rho_\infty, T_\infty)}{3}\right)\eta f(M) , \qquad (3)$$

where $n_{\rm BH} \approx 0.01\, M_\odot$ pc^{-3} is the local dark matter halo density (Gates, Gyuk, & Turner 1995), Ω is the solid angle of sky coverage, $d_{\rm max}$ is the maximum distance to which the SDSS can

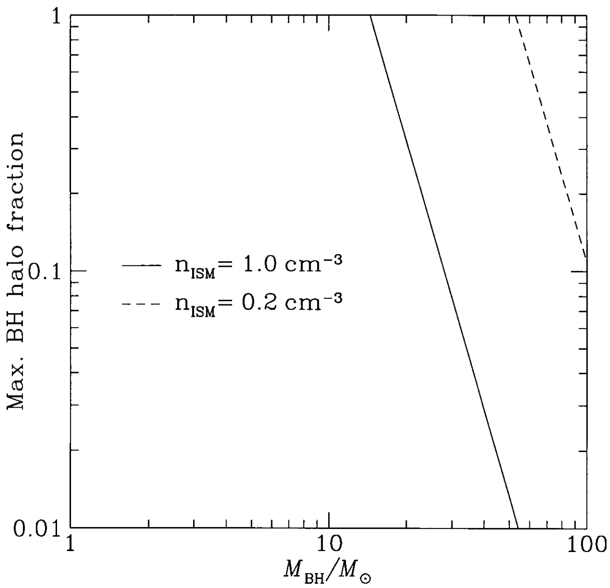

FIG. 3.—Maximum halo mass fraction in black holes if no black hole candidates are found with the SDSS, for two values of the ISM density. For $M \gtrsim 10\ M_\odot$, the SDSS is sensitive to black holes beyond the local bubble, where one expects $\bar{n}_{ISM} \sim 1\ \mathrm{cm}^{-3}$.

observe the spectrum of a black hole to a limiting r magnitude of $m_r = 20$, and $f(M)$ is the fraction of the halo with black holes of mass M. The factor η accounts for the fact that the black holes in the halo will have a high velocity with respect to the ISM. The luminosity is a very sensitive function of velocity (see eq. [1]); thus we include only those black holes with velocity $\boldsymbol{v}$ such that $|\boldsymbol{v} - \boldsymbol{V}| < a_\infty$, where $\boldsymbol{V}$ is the local velocity of the disk. We use the simple model of a nonrotating halo which has a locally isotropic and Maxwellian distribution with an average velocity of 270 km s^{-1}. Then η is the fraction of the population with $|\boldsymbol{v} - \boldsymbol{V}| < a_\infty$. For $T_\infty = 10^4$ K, $\eta \approx 10^{-4}$. By setting $N_{obs} \leq 1$, using $\Omega = \pi$, and assuming 100% detection efficiency, we obtain the result for $f(M)$ shown in Figure 3. Note that the SDSS will be very sensitive to black holes of mass $M \gtrsim 10\ M_\odot$.

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