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CAN ISOLATED STELLAR-MASS BLACK HOLES EXPLAIN THE HARD X-RAY SOURCES IN THE GALACTIC CENTER REGION?

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ABSTRACT

It has been proposed that the X-ray source 1E 1740.7−2942 might be the first example of an isolated stellar-mass black hole directly accreting from a molecular cloud. This scenario rests on the unusual radio, IR, and γ-ray properties of 1E 1740.7−2942 and on its spatial coincidence with one of the dense molecular clouds of the Galactic center region. Based on a model for the birth rate of compact stellar remnants and their evolution in the Galactic gravitational potential, we estimate the probability of such an association. Although the conditions in the Galactic center regions are the most favorable for the presence of neutron stars and black holes inside dense molecular clouds, the requirements necessary to allow a sufficiently high accretion rate strongly reduce the probability of observing these kind of objects.

Subject headings: accretion: accretion disks — black hole physics — ISM: clouds — stars: individual: 1E 1740.7−2942, GRS 1758−258 — X-rays: stars

1. INTRODUCTION

The possibility of observing compact objects (neutron stars or black holes) accreting from the interstellar medium (ISM) has attracted considerable attention since the early theoretical works on this problem (Hoyle & Lyttleton 1939; Bondi 1952) and especially after the discovery of the X-ray sources in the 1960s (see, e.g., Treves, Maraschi, & Abramowicz 1989 and references therein). The mass accretion rates, and therefore the X-ray luminosities, depend essentially on the velocity of the compact object relative to the accreting medium and on the density of the latter. Under typical conditions in the ISM, the predicted luminosities are of the order 10^{28}–10^{31} ergs s^{-1}, several orders of magnitude smaller than in the case of neutron stars or black holes accreting from close companions in binary systems. Recent reevaluations of this problem have been stimulated by the all-sky surveys and deep, sensitive pointings now available in the soft X-ray range thanks to the *ROSAT* and *EUVE* satellites (Treves & Colpi 1991; Blaes & Madau 1993, hereafter BM). These works have shown that a large number of old neutron stars accreting from the ISM should be detectable, but none has been identified so far.

A greater accretion rate is predicted for compact objects in dense molecular clouds ($n \gtrsim 10^3$ H cm^{-3}), which therefore should be more promising places to look for such sources (BM; Campana & Pardi 1993; Colpi, Campana, & Treves 1993). For some time, the X-ray pulsar H0253+193 was thought to be the first example of an isolated neutron star (or white dwarf) accreting from a molecular cloud (Halpern & Patterson 1987; Bhatt 1990). However, recent infrared observations (Zuckerman et al. 1992) showed that this object is a distant cataclysmic variable, aligned by chance with the core of the nearby cloud Lynds 1457.

Several authors have recently suggested that the hard X-ray source 1E 1740.7−2942 (also sometimes called "the Great Annihilator" or "the miniquasar") might be an isolated black hole accreting from a molecular cloud (Bally & Leventhal 1991; Mirabel et al. 1991). This proposal is based on the unusual properties of this source (briefly reviewed in § 2) and on its spatial coincidence with a molecular cloud observed at millimeter wavelength. The high concentration of both molecular clouds and old, degenerate stellar remnants in the central region of the Galaxy has been invoked to explain the fact that this unique object is located close to the Galactic center. Here we present the results of a detailed computation of the probability of finding a black hole/molecular cloud association in the Galactic center region (§ 3). Despite the uncertainties involved in the models used, it turns out that this probability is quite small, and, therefore, other explanations for 1E 1740.7−2942 should not be discarded a priori.

2. THE PECULIAR SOURCE 1E 1740.7−2942

2.1. *Why a Black Hole?*

At soft X-ray energies (~1–3.5 keV), the range in which this source was discovered (Hertz & Grindlay 1984), 1E 1740.7−2942 is a relatively faint emitter, similar to the other few tens of sources observed within a few degrees from the Galactic center direction. However, contrary to the other sources which are likely to be neutron star binaries, the spectrum of 1E 1740.7−2942 is very hard, extending up to several hundred keV, where it dominates the emission from this region of sky (Skinner et al. 1991; Sunyaev et al. 1991). This spectral shape is very similar to that of the normal ("low/hard") state of Cyg X-1, which, among the persistent X-ray sources, is considered the best black hole candidate. Assuming for 1E 1740.7−2942 a distance of the order of the Galactic center (~8.5 kpc), the two sources are also similar in absolute X-ray luminosity, ~(2–4) × 10^{37} ergs s^{-1} (in the 35–300 keV energy range).

Further evidence for the black hole nature of 1E 1740.7−2942 came from the SIGMA discovery of a transient, broad spectral feature in the 300–600 keV range (Bouchet et al. 1991), reminiscent of the "MeV bump" observed in Cyg X-1 with the *HEAO 3* satellite in 1979 (Ling et al. 1987). This feature is probably related to the presence of a hot electron-positron–pair plasma and led also to the suggestion that 1E 1740.7−2942 might be responsible for the variable component

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of the 511 keV annihilation radiation coming from the Galactic center direction (Lingenfelter & Ramaty 1989; Ramaty et al. 1992).

At centimeter wavelengths, 1E 1740.7−2942 consists of a time-variable point source ($\sim$0.5 mJy) with two symmetrical radio jets (Mirabel et al. 1992). The jets extend for about 30″ ($\sim$1 pc) and terminate with edge-brightened radio lobes, thus giving to the source the appearance of a miniature radio galaxy. Although radio emission is not uncommon in Galactic X-ray binaries (see, e.g., Hjellming & Penninx 1991), the morphological radio structure of 1E 1740.7−2942 is rather peculiar.

All these characteristics and analogies are indeed strongly suggestive of the presence of an accreting black hole. We note, however, that a firm piece of evidence, based on a dynamic mass measurement, as, for instance, in the black hole candidates A0620−00, GS 2023+33, and GS 1124−68 (Stella 1993), is not available for 1E 1740.7−2942. In the following we will thus also consider the possibility of an isolated neutron star.

2.2. *Why Isolated*?

The accurate positioning of 1E 1740.7−2942 (< 1″) obtained with the VLA observations of its radio core made a search for an optical and infrared counterpart feasible. Optical observations are strongly limited by the heavy interstellar absorption in this direction (Mereghetti et al. 1992), but deep searches in the infrared, less affected by this problem, also failed to detect any object at the radio position, with limits of $K = 17$ and $L = 13$ (Djorgowski et al. 1992; Mirabel & Duc 1992). These limits rule out the presence of a giant or supergiant companion, unless the absorption is greater than $A_V \sim 40$, and/or the source is much farther than the Galactic center. If $A_V \sim 20$, main-sequence stars earlier than spectral type A are also excluded. Thus, for any reasonable assumption on the distance and absorption, only a low-mass companion is allowed. However, all the black hole candidates in low-mass X-ray binaries are transient sources (see, e.g., Mereghetti 1993), while 1E 1740.7−2942, although variable, never showed the typical outbursts with the fast rise and exponential decay characteristic of these ultrasoft transients.

If 1E 1740.7−2942 is not accreting from a binary companion, the only source of material capable of powering it is the dense molecular cloud (Bally & Leventhal 1991), whose peak in the millimeter emission lies only $\sim$40″ away. Mirabel et al. (1991) have mapped this cloud in the high-density tracer lines of HCO^+ and CS and have shown that it belongs to the molecular cloud complex of the Galactic center region.

3. THE NUMBER OF COMPACT OBJECTS IN THE GALACTIC CENTER REGION

The birth rate of compact stellar remnants in the central part of the Galaxy can be estimated by assuming an initial mass function (IMF) and a star formation history (SFH). Since the molecular clouds layer in the Galactic center region has a typical scale height of only $\sim$40 pc, it is necessary to take into account the vertical dispersion of the compact remnants resulting from their high spatial velocities. In addition, the expected accretion rate depends critically on the velocity of the compact objects relative to the ISM. We have therefore performed a Monte Carlo simulation to obtain the present distribution of velocities and heights of this population, under the influence of the Galactic gravitational potential.

Our simulation is similar to those recently developed for accreting neutron stars (Paczyński 1990; Hartmann, Epstein, & Woosley 1990; BM): we consider an initial population, with assigned positions and velocities, and let it evolve in the Galactic gravitational potential. We have assumed a Galactic potential consisting of the sum of a halo, a spheroid, and a disk component with the same numerical parameters as BM. To calculate the relative number of compact objects, we have used a recently proposed IMF (Ferrini, Palla, & Penco 1990), which is steeper at the high-mass end than the usual Salpeter's IMF. The limiting masses for the progenitor stars that we have adopted are 6 and 25 $M_\odot$, respectively, for the formation of neutron stars and black holes (Maeder 1992). The absolute number of compact objects produced by the stellar evolution depends on the assumed SFH of the Galaxy. Ferrini et al. (1992) derived a SFH from a multiphase model for the evolution of spiral galaxies. This model, based on the observed chemical and stellar properties in the solar cylinder, gives the SFH in the vicinity of the Sun. For simplicity, and for lack of better estimates, we have extended it to the whole Galaxy (for more details, see Campana and Pardi 1993).

We have performed the calculations for two different radial distributions of initial positions of the stellar remnants, $p(R)$. In the first model (model A) we adopted the same distribution used by BM, i.e., $p(R) \propto R \exp(-R)$, where R is the galactocentric radius. For this model, which probably underestimates the progenitor density in the Galactic center region, we have computed the neutron star and black hole surface density averaged over the whole Galaxy. In the second model (model B) we have considered a radial probability distribution which gives greater weight to the central region of the Galaxy, i.e., a Gaussian with $\langle R \rangle = 5$ kpc and $\sigma_R = 2$ kpc (Hartmann et al. 1990). In this case, we have computed the neutron star and black hole surface density in the region of interest, namely, the central $\sim$500 pc of the Galaxy. In both models, we adopted an initial vertical dispersion given by a Gaussian with $\langle z \rangle = 0$ pc and $\sigma_z = 60$ pc, which is the scale height for OB stars, and a Gaussian distribution of initial velocities with $\langle v \rangle = 0$ km s^{-1} and $\sigma_v = 100$ km s^{-1}, isotropic in the local standard of rest. This high velocity dispersion is comparable to that measured for radio pulsars, which is reasonably well known (Lyne et al. 1982; Harrison, Lyne, & Anderson 1992). On the other hand, the velocity distribution for black holes is unknown. For this reason we have also performed the computations in both models with a smaller velocity dispersion, $\sigma_v = 10$ km s^{-1}.

The results are summarized in Table 1, which gives the surface density (in objects per square parsec) of neutron stars and black holes within 40 pc of the Galactic plane.

4. DISCUSSION

The molecular clouds in the central part of the Galaxy are denser ($n \gtrsim 10^3$ cm^{-3}) and hotter than those in the outer regions (e.g., Bally et al. 1987, 1988). Also, their filling factor f,

TABLE 1

Surface Density (pc^{-2}) of Black Holes and Neutron Stars

Objects	Model A[a]	Model B[b]
Black holes ($\sigma_v = 100$ km s^{-1})	0.003	0.008
Black holes ($\sigma_v = 10$ km s^{-1})	0.013	0.021
Neutron stars ($\sigma_v = 100$ km s^{-1})	0.058	0.171

[a] Average over the whole Galaxy.

[b] Only within $R = 500$ pc.

defined as the fraction of volume occupied by molecular clouds, is higher than in the rest of the Galaxy. In the solar neighborhood $f_s \sim 1\%$, while within ~ 500 pc from the center, we have $f_c \sim 10\%$. If we consider only the regions with the highest densities, we can estimate a filling factor $f_{cd} \sim 0.05\%$ (Mirabel et al. 1991), which is still a factor 100–1000 greater than the corresponding value for the solar neighborhood (Böhringer, Morfill, & Zimmermann 1987). Therefore, based on the results of the previous section (Table 1), we expect between about one and ~ 10 black holes and between ~ 20 and ~ 70 neutron stars in the densest regions of the inner ~ 500 pc of the Galaxy.

If 1E 1740.7−2942 is at the Galactic center distance, an accretion rate capable of producing a total X-ray luminosity of $\lesssim 10^{38}$ ergs s^{-1} is required. In the black hole case, assuming an efficiency of 10%, this translates to a limit on the relative (cloud–black hole) velocity of ~ 10 km s^{-1}. This value is derived by using the classic accretion rate prescriptions of Bondi (1952), with a cloud density of $n = 10^5$ cm^{-3} and a black hole mass of $M = 10\ M_\odot$ (obviously raising n and/or M, higher velocities are allowed). Spherical accretion onto black holes is highly inefficient ($\epsilon \ll 10\%$); however, due to turbulent motions in the molecular cloud, an accretion disk might form, thus considerably increasing the efficiency of the accretion process. With the conservative assumption that the length scale of turbulent motions for molecular clouds is the same as that for the normal ISM, it can be shown that, for $M = 10\ M_\odot$, an accretion disk can be formed for relative velocities smaller than ~ 25 km s^{-1} (McDowell 1985). Incidently, the formation of an accretion disk is probably also required to explain the presence of the radio jets observed in 1E 1740.7−2942.

Our simulations permit us to compute the final velocity distribution of the remnants which remain within 40 pc from the Galactic plane. Indeed, as a result of the influence of the Galactic potential, the fraction of slowly moving objects can be substantially different with respect to the initial distribution (see also BM). In the most favorable case (model B), only 4% of black holes with $|z| < 40$ pc have velocities smaller than 10 km s^{-1}, for $\sigma_v = 100$ km s^{-1}, and 34%, for $\sigma_v = 10$ km s^{-1}. Thus, only if most of the black holes have small initial velocities do we expect a few (about 3) of them in the densest region of molecular clouds accreting at a sufficiently high rate. On the other hand, if the velocity dispersion of black holes is similar to that observed for radio pulsars, the probability of seeing one of these objects is smaller ($\sim 10\%$ in the most favorable case).

In view of the lack of dynamic evidence for a black hole in 1E 1740.7−2942, we also consider the neutron star case, which should, in principle, be more likely (Table 1). In this case, a very small relative velocity is required ($\lesssim 3$ km s^{-1}), because of the lower mass of neutron stars. Our simulations show that the fraction of neutron stars with velocities sufficiently small is $\lesssim 0.01$. In addition, other problems arise, since v is in this case comparable to the sound speed in the cloud (assuming $T \sim 100$ K), which therefore cannot be neglected in the expression for the gravitational accretion radius. In this situation, it may happen that the gas thermal velocity drives the effective accretion rate, causing a smaller accretion and a fainter source. We also note that such a small relative velocity is also unlikely because of the gravitational attraction exerted on the neutron star by the cloud itself.

5. CONCLUSIONS

Our results indicate that despite the great density of molecular clouds in the central part of the Galaxy, the number of isolated compact objects that we can see as strong X-ray sources is indeed quite small and can even be null. The unknown parameter on which our simulations are more sensitive is the initial velocity dispersion of the black holes. A small value of σ_v would be favored by the identification of several objects with properties similar to those of 1E 1740.7−2942. In this respect, another possible candidate deserving further investigation could be the hard X-ray/radio source GRS 1758−258 (Sunyaev et al. 1991, Mereghetti et al. 1992, Rodríguez, Mirabel, & Martí 1992). Despite the unavoidable uncertainties, our quantitative analysis thus confirms the remark by Mirabel et al. (1991): "It is perhaps more unsettling on statistical grounds that there be a single such object, rather than either many or zero."

The hard X-ray source 1E 1740.7−2942 remains so far the best candidate for an isolated black hole accreting from a molecular cloud, but other observations are needed to rule out more standard and more probable models. In particular, a detailed analysis of its short/medium term X-ray variability is still lacking. We expect this to be the most promising way to investigate this object, given the obvious difficulties in its optical/IR studies, and the less conclusive inferences on the nature of the accreting star that can be drawn from X-ray spectral investigations.

Our simulations also show that there is a large number of compact remnants with velocities too high to power $\sim 10^{37}$–10^{38} ergs s^{-1} luminosity sources but which, nevertheless, remain within the molecular gas scale height and whose effects have not been considered in detail so far. Some of these objects might be detectable individually as faint and strongly absorbed sources by the next generation of X-ray instruments. As a population, they might produce a detectable diffuse emission, mainly originating from the "intracloud" remnants. There is in fact evidence that, in addition to the gas in dense clouds, the ISM in this region has density high enough (~ 100 cm^{-3}) to yield luminosities $\sim 10^{30}$ ergs s^{-1} (for a neutron star with $v \sim 80$ km s^{-1}). Considering the high number of such objects, they could contribute significantly to the diffuse hard X-ray emission observed from the Galactic center region (Skinner et al. 1987).

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