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Reviewed work(s):
Source: *Publications of the Astronomical Society of the Pacific*, Vol. 112, No. 769 (March 2000), pp. 297-314
Published by: The University of Chicago Press on behalf of the Astronomical Society of the Pacific
Stable URL: http://www.jstor.org/stable/10.1086/316529
Accessed: 17/10/2012 08:45

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **112**:297–314, 2000 March

Invited Review

Isolated Neutron Stars: Accretors and Coolers

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Received 1999 November 19; accepted 1999 November 20

ABSTRACT. As many as 10^9 neutron stars populate the Galaxy, but only $\approx 10^3$ are directly observed as pulsars or as accreting sources in X-ray binaries. In principle, also the accretion of the interstellar medium may make isolated neutron stars shine, and their weak luminosity could be detected in soft X-rays. Recent *ROSAT* observations have convincingly shown that neutron stars accreting from the interstellar medium are extremely rare, if observed at all, in contrast with earlier theoretical predictions. Until now two possible explanations for their elusiveness have been proposed: their velocity distribution may peak at $\sim$200–400 km s^{-1}, as inferred from pulsar statistics, and this would severely choke accretion; the magnetic field may decay on timescales $\sim 10^8$–10^9 yr, preventing a large fraction of neutron stars from entering the accretor stage. The search for accreting neutron stars has produced up to now a handful of promising candidates. While little doubt is left that these objects are indeed isolated neutron stars, the nature of their emission is still controversial. In particular, accreting objects can be confused with much younger, cooling neutron stars. However, a combination of observations and theoretical modeling may help in discriminating between the two classes.

1. INTRODUCTION

Neutron stars (NSs) are a well-established endpoint of stellar evolution. Although their existence was proposed in the 1930s, their actual discovery coincides with that of pulsars and with the recognition that pulsars are young, rapidly spinning NSs, endowed with a large magnetic field. A few years later it was realized that most X-ray binaries, and X-ray pulsators in particular, do contain accreting NSs.

Altogether observed pulsars and X-ray binaries account for $\sim$1500 objects. However, as indicated by various arguments (see § 4), NSs should represent a nonnegligible fraction, $\sim$1%, of the stars in the Galaxy, with a total number as high as 10^9. NSs are, therefore, rather numerous but extremely elusive.

Let us consider isolated NSs, which supposedly represent the bulk of the population. Soon after their birth they may show up as radio pulsars, if the beaming conditions are favorable, and the pulsar phase may last some 10^7 yr. At formation NSs are hot ($T \sim 10^{11}$ K), and they may give off thermal radiation while cooling. Pulsar activity may contribute to the warming, but after a few tens of millions of years the supply of energy, both rotational and internal, will be essentially exhausted. From then on, NSs are cold, dead objects, apart for some sudden release of internal energy, such as seismic activity, which has been often proposed but never convincingly observed. Since the Galaxy is $\sim 10^{10}$ yr old, one infers that the active state of NSs is a tiny fraction of their life or, conversely, that the Galaxy is the graveyard of a multitude of dead NSs.

The dowry of collapsed objects is their gravitational field, which in the case of NSs is strong, since their radius is about 3 gravitational radii. NSs in the Galactic halo may become responsible for lensing episodes, and in fact they have been invoked in that context (see, e.g., Wasserman & Salpeter 1994). Also, many investigations suggest that the magnetosphere of old NSs accreting from dense clouds may be bounded by a collisionless shock (see, e.g., Arons & Lea 1976), although a self-consistent analysis probing its existence has not been presented yet. In this picture, the Alfvén radius could be a possible site for acceleration of cosmic rays (Shemi 1995). Inelastic *p*-*p* collisions between the accelerated particles and the accreting flow may also produce 300 GeV–1 TeV γ-rays, which may be detected by Cerenkov experiments (Blasi 1996). However, although these remain promising possibilities, up to now no NS has been detected unambigously through these techniques.

Dead neutron stars may, however, be brought to life again by accretion from the interstellar medium (ISM). This idea, which is the main guideline of this review, was proposed some 30 years ago by Ostriker, Rees, & Silk (1970, hereafter ORS), but for two decades it remained latent in the impetuous progress of X-ray astronomy. It was only in the early 1990s that Treves & Colpi (1991, hereafter TC) and Blaes & Madau (1993, hereafter BM) realized that the *ROSAT* X-ray telescope (launched in 1990 May) could have the capability of detecting NSs accreting from the ISM. These conclusions motivated a renewed interest in the field, and several studies aiming to estimate the number of detectable sources in the more favorable sites in the Galaxy were presented.

It has become increasingly clear that a realistic estimate of the observability of old, isolated, accreting neutron stars (ONSs) relies on a thorough understanding of a number of issues, such as the following:

1. The present density and velocity distribution of NSs, a subject of interest in itself, strongly related to pulsars' birth rate and kick distribution. The accretion rate is, in fact, inversely proportional to the star velocity cubed.
2. The magnetic field and spin evolution of isolated NSs, an unsolved problem in compact object astrophysics. Their knowledge is crucial for old neutron stars, since accretion onto a rotating dipole depends critically on the field strength and the rotation period.
3. The distribution of the interstellar medium and giant molecular clouds in the Galaxy. The ONS luminosity scales linearly with the density of the ambient medium, so brighter sources are found where the ISM is denser.
4. The spectral properties of radiation emitted by neutron stars accreting at low rates, and their dependence on the magnetic field.

There has been substantial progress in all these fields over the last few years.

Spectra from accreting NSs for very low luminosities have been computed for both unmagnetized and magnetized atmospheres by Zampieri et al. (1995) and Zane, Turolla, & Treves (2000). This regime was never explored before, since attention was mainly focused on X-ray binaries, where the luminosity is not far from the Eddington limit, millions of times that expected from ONSs accreting from the ISM (see § 3).

The present distribution of NSs has been studied by several authors (Paczýnski 1990; Blaes & Rajagopal 1991; BM; Zane et al. 1995) and led to the prediction that a large number of accreting ONSs should be detectable with *ROSAT* in regions where the ISM is denser, such as the closer giant molecular clouds (BM; Colpi, Campana, & Treves 1993; Zane et al. 1995) or in the solar vicinity (Zane et al. 1996c). It was also suggested that the collective emission from the ONS population could account for part of the Galactic excess in the soft X-ray background (Zane et al. 1995) and for the soft component of the diffuse X-ray emission from the Galactic center (Zane, Turolla, & Treves 1996b).

However, as soon as the first results of the searches for isolated NSs were published (Motch et al. 1997; Belloni, Zampieri, & Campana 1997; Maoz, Ofek, & Shemi 1997; Danner 1998a, 1998b), it became apparent that theoretical estimates were in excess by a factor at least 10–100 over the upper limits implied by observations. Still, in the last few years half a dozen objects found in *ROSAT* images appear as good candidates for close-by ONSs accreting from the ISM (Stocke et al. 1995; Walter, Wolk, & Neuhäuser 1996; Haberl et al. 1996, 1997; Haberl, Motch, & Pietsch 1998; Schwope et al. 1999; Motch et al. 1999; Haberl, Pietsch, & Motch 1999).

The most recent line of research is therefore twofold. First, it aims to explain the paucity of observed ONSs. At present, the most likely answers to this puzzling question are that NSs have a much larger mean velocity than that assumed in the past (so the luminosity is drastically reduced) or that the magnetic field decays over a timescale $\approx 10^8$–10^9 yr (preventing the star from entering the accretion stage). In both cases upper limits on the number of observable ONSs can be used to constrain the population properties (Colpi et al. 1998; Livio, Xu, & Frank 1998; Popov et al. 1999). The second goal is to provide a definite assessment of the nature of the seven candidates proposed so far. Although their identification with isolated NSs seems rather firm, it is still unclear if they are rather young cooling objects, giving off thermal radiation at the expense of their internal energy, or accreting ONSs. Definite proof may come from observations at optical wavelengths, where the two classes of sources should show rather distinct emission properties (Zane et al. 2000).

New-generation X-ray satellites (*Chandra*, *XMM*, *Astro-E*), may either increase the number of ONS candidates or lend further support to their paucity. Since these new missions are becoming operational, it seems appropriate to review now our present knowledge of the subject.

The structure of the paper is the following. In § 2 we summarize the basic conditions under which accretion is possible, and § 3 contains a discussion about the spectral properties. The conditions affecting the number of old, accreting NSs are analyzed in § 4. Section 5 reviews theoretical investigations about the observability of single sources. A report of the present status of observations is given in § 6, and the observational appearance of accreting and cooling NSs is discussed in § 7. In § 8 possible explanations for the paucity of accretors are considered. Our conclusions follow in § 9.

2. INTERACTION WITH THE INTERSTELLAR MEDIUM: VARIOUS TYPES OF NSs

Let us consider a NS of mass M, radius R, spin period P, magnetic field B, moving with velocity V relative to an ambient medium of number density n. There are various possible modes of interaction between the NS and the medium (see, e.g., Davidson & Ostriker 1973; Lipunov 1992; and, specifically for the case of isolated NSs, Treves et al. 1993; Popov et al. 1999), and these are well illustrated by introducing different characteristic lengths. The most relevant ones are the accretion, the corotation, and the Alfvén radius, all of them familiar from the theory of binary X-ray sources.

The accretion radius, $r_{\rm acc}$, defines the region where the dynamics of the ISM are dominated by the gravitational field of the NS and is given by

$$r_{\rm acc} = \frac{2GM}{v^2} \sim 3 \times 10^{14} m v_{10}^{-2} \text{ cm} , \qquad (1)$$

where $v_{10} = (V^2 + C_s^2)^{1/2}/(10 \text{ km s}^{-1})$ and $m = M/M_\odot$, where $M_\odot$ is the solar mass and $C_s \sim 10 \text{ km s}^{-1}$ is the ISM sound speed. Equation (1) is derived in the framework of the Hoyle-Bondi theory of accretion. The resulting value of $r_{\rm acc}$ is only approximate, but it is sufficient for our purposes.

Similarly, the Alfvén radius, $r_{\rm A}$, is the boundary inside which the dynamics of the infalling matter is dominated by the NS magnetic field. In spherical symmetry,

$$r_{\rm A} = \left(\frac{B^2 R^6}{\sqrt{2GM}\dot{M}}\right)^{2/7} \sim 2 \times 10^{10} B_{12}^{4/7} \dot{M}_{11}^{-2/7} R_6^{12/7} m^{-1/7} \text{ cm} , \qquad (2)$$

where $\dot{M}$ is the accretion rate (see eq. [10]), $B_{12} = B/(10^{12}$ G), $\dot{M}_{11} = \dot{M}/(10^{11} \text{ g s}^{-1})$, and $R_6 = R/(10^6$ cm).

Finally, the corotation radius is obtained by equating the angular velocity of the NS with the Keplerian angular velocity,

$$r_{\rm co} = \left(\frac{GMP^2}{4\pi^2}\right)^{1/3} \sim 2 \times 10^8 m^{1/3} P^{2/3} \text{ cm} . \qquad (3)$$

In the case of an NS, strong magnetic fields and fast rotation may inhibit accretion because of the momentum outflow, produced by the spinning dipole, and the corotating magnetosphere (ORS; Illarionov & Sunyaev 1975; Davies & Pringle 1981; Blaes et al. 1992). Three basic conditions must be verified in order to make accretion possible. First, accretion is inhibited if the Alfvén radius is larger than the accretion radius, in which case the system remains in the so-called *georotator* stage.

Second, at the accretion radius the gravitational energy density of the incoming material,

$$U_G = \frac{GMm_p n}{r} \sim 6.5 \times 10^{-13} \dot{M}_{11} r_{14}^{-5/2} \text{ ergs cm}^{-3} , \qquad (4)$$

must be greater than the energy density, U_B, of the relativistic momentum outflow produced by the rotating B field. If the field is dipolar,

$$U_B = \left(\frac{B^2}{8\pi}\right)\left(\frac{R^6}{r_c^6}\right)\left(\frac{r_c^2}{r^2}\right) \sim 7.5 \times 10^{-9} B_{12}^2 P^{-4} R_6 r_{14}^{-2} \text{ ergs cm}^{-3} , \qquad (5)$$

where $r_{14} = r/(10^{14}$ cm) and $r_c = cP/2\pi$ is the light cylinder radius. This condition is met only when the NS has spun down to a period

$$P \gtrsim P_{\rm crit} \sim 10\ B_{12}^{1/2} \dot{M}_{11}^{-1/4} (r_{\rm A})_{14} R_6^{3/2} m^{-1/8} \text{ s} , \qquad (6)$$

while during the time in which $P < P_{\rm crit}$ the system is in the *ejector* phase, with no accretion occurring. The duration of this phase may largely exceed the pulsar lifetime ($\sim 10^7$ yr).

Since the star is slowing down at the magnetic dipole rate, this first barrier is overcome in a typical timescale $t_1 \sim 4 B_{12}^{-1} \dot{M}_{11}^{-1/2}$ Gyr. As noted by BM, this value is uncomfortably close to the age of the Galaxy. However, if taken literally, it implies that a large fraction of ONSs can have spun down sufficiently, at least if the majority of them are born early in the Galactic history.

After P has increased above $P_{\rm crit}$, the infalling material proceeds undisturbed until the Alfvén radius, where the NS magnetic energy density balances the matter bulk kinetic energy density. The corotating magnetosphere will then prevent the accreting material from going any farther, unless the gravitational acceleration at the Alfvén radius is larger than the centrifugal pull, i.e.,

$$\frac{GM}{r_{\rm A}^2} \gtrsim \left(\frac{2\pi}{P}\right)^2 r_{\rm A} . \qquad (7)$$

This translates into another stronger constraint on the value of the period, since it must be

$$P \gtrsim P_{\rm A} \sim 10^3 B_{12}^{6/7} \dot{M}_{11}^{-1/2} m^{-1/2} \text{ s} \qquad (8)$$

(our third condition), otherwise matter will accumulate at

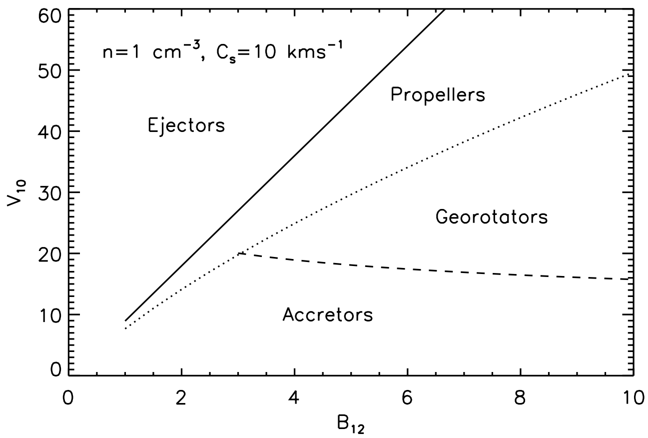

FIG. 1.—Different stages of an old neutron star as a function of the star velocity, in units of 10 km s^{-1}, and magnetic field, in units of 10^{12} G.

the Alfvén radius and the system remains in the so-called *propeller* phase.

The centrifugal barrier at the Alfvén radius poses a severe problem, since P_A is so large that it cannot be reached only by means of magnetic dipole radiation. However, there are at least two other effects that may play an important role, making accretion possible: the decay of the B field and the torque exerted by the accreting material on the NS itself. The accreted matter will be spun up by the magnetosphere, and it will exert a torque on the NS (see, e.g., BM). The propeller physics is very complicated, and a detailed review of this issue is outside the scope of this paper. Its thorough understanding requires a full two-dimensional or even three-dimensional MHD investigation of the interaction between accretion flow and rotating magnetosphere (see, e.g., Toropin et al. 1999). Nevertheless, approximated expressions for the torque were presented by BM (see also, for other spin-down formulae, Lipunov & Popov 1995). Based on that treatment, the corresponding spin-down time to P_A turns out to be $\sim 0.04 B_{12}^{-11/14} n^{-17/28} v_{10}^{29/14}$ Gyr, a value adequate to allow interstellar accretion even for high values of the magnetic field. However, for such high fields accretion is probably unsteady and ONSs might appear as transient X-ray sources (Treves et al. 1993). Numerical simulations indicate that more rapid spin-down occurs either because of the large mass expulsion rate (Toropin et al. 1999; Yu. M. Toropin 1999, private communication) or because the material builds up, compressing the magnetosphere and becoming unstable to large-scale mixing with the B field (Wang & Robertson 1985).

In any case, if the second barrier is also overcome, then matter flows down onto the NS surface and the system becomes an *accretor*. Eventually, at least in the simplest picture, if the magnetic field is strong enough to channel the accretion flow, the gas slides along the open field lines and the emitting region is restricted to two polar caps of radius

$$r_{\rm cap} \sim \frac{R^{3/2}}{r_A^{1/2}} \sim 7 \times 10^3 B_{12}^{-2/7} \dot{M}_{11}^{1/7} R_6^{9/14} m^{1/14}\ {\rm cm}\ . \quad (9)$$

The accretion rate is a sensitive function of the star velocity and, again within the Bondi-Hoyle theory, is given by

$$\dot{M} = \frac{2\pi (GM)^2 m_p n}{(V^2 + C_s^2)^{3/2}} \sim 10^{11} n v_{10}^{-3}\ {\rm g\ s^{-1}}\ . \quad (10)$$

The total luminosity is then

$$L \sim \frac{GM}{R} \dot{M} \sim 2 \times 10^{31} \dot{M}_{11}\ {\rm ergs\ s^{-1}}\ , \quad (11)$$

which is orders of magnitude below the Eddington limit. This implies that matter is very nearly in free fall until it reaches the NS surface. The dynamical time is then much shorter than the radiative cooling times, and virtually no energy is released before the flow hits the outermost stellar layers. Here accreting protons are decelerated by Coulomb collisions with atmospheric electrons and/or by plasma interactions, and the flow stops after penetrating a few ($\lesssim 10$) Thomson depths in the NS atmosphere. The bulk kinetic energy of the infalling protons is transformed into thermal energy and finally converted into electromagnetic radiation.

An example of the possible stages for a 10 Gyr old NS as a function of the star velocity and magnetic field is shown in Figure 1.

3. THE SPECTRUM OF ACCRETING NSs

Because of the combined effects introduced by the response of the detector and absorption by the ISM, theoretical estimates on ONS observability and the choice of the most favorable energy bands for their detection are crucially related to the determination of the spectral properties of the emitted radiation and to the evaluation of the mean photon energy in particular.

3.1. Blackbody Spectrum

Many investigators assumed (and still do!) that the spectrum emitted by NSs accreting from the ISM is a blackbody at the star effective temperature,

$$T_{\rm eff} = \left(\frac{L}{4\pi f R^2 \sigma}\right)^{1/4} \sim 3.4 \times 10^5 L_{31}^{1/4} R_6^{-1/2} f^{-1/4}\ {\rm K}\ , \quad (12)$$

where f is the fraction of the star surface covered by accretion and $L_{31} = L/(10^{31}$ ergs s$^{-1})$ (see eq. [11]). Although crude, such approximation is basically correct, since the density in the deep atmospheric layers for $T \sim T_{\rm eff}$ turns out to be

$$\rho \approx \frac{GMm_p \tau_{\rm es}}{R^2 kT_{\rm eff}} \sim 16\tau_{\rm es} m R_6^{-2} (T_{\rm eff})_5^{-1} \text{ g cm}^{-3} , \quad (13)$$

where $(T_{\rm eff})_5 = T_{\rm eff}/(10^5$ K). For these values of density and temperature, the free-free optical depth $\tau_{\rm ff} \approx (\kappa_{\rm ff}/\kappa_{\rm es})\tau_{\rm es}$ is much larger than unity up to $h\nu \gg kT_{\rm eff}$, so thermal equilibrium is established. Compton scattering is not expected to modify the spectrum because of the relatively low Thomson depth and electron temperature. Cold atmospheric electrons emit cyclotron radiation, but for $B \sim 10^9$ G the cyclotron line contribution to the total luminosity is vanishingly small and it never exceeds a few percent even for $B \sim 10^{12}$ G (Nelson et al. 1995). These considerations show that, at least to first order approximation, the emission is peaked at an energy

$$E \sim 3kT_{\rm eff} \sim 100\ L_{31}^{1/4} R_6^{-1/2} f^{-1/4} \text{ eV} , \quad (14)$$

which falls in the soft X-ray range (see ORS).

For a low magnetic field ($B \lesssim 10^{10}$ G) emission/absorption processes (and radiative transfer) are much the same as in the nonmagnetic case, but the emitting area is now substantially reduced because $r_{\rm cap} \ll R$. This has an important effect on the emitted spectrum, since, for a given luminosity, the effective temperature increases with decreasing f

$$\frac{T_{\rm eff}}{T_{{\rm eff},B=0}} = f^{-1/4} = \left(\frac{4\pi R^2}{2\pi r_{\rm cap}^2}\right)^{1/4} \sim 13 B_{12}^{1/7} \dot{M}_{11}^{-1/14} R_6^{5/28} m^{-1/28} . \quad (15)$$

Of course, the same argument about the reduced size of the radiating region holds also for strongly magnetized NSs ($B > 10^{10}$ G), although in the latter case the different response properties of the magnetoactive plasma must be accounted for.

The typical values of $T_{\rm eff}$ and L indicate the two basic reasons that make the detection of these sources extremely difficult: their intrinsic weakness (the luminosity is orders of magnitude below solar), and the fact that their spectrum peaks in the EUV–soft X-rays, an energy band which is strongly absorbed and not easily accessible even to spaceborne instrumentation. A definite prediction, which is largely independent of the details of the spectral distribution, is that the X-ray–to–optical flux ratio must be exceedingly large for these sources,

$$\log\left(\frac{f_{\rm X}}{f_V}\right) \sim 5.5 + 3 \log\left(\frac{kT_{\rm eff}}{100 \text{ eV}}\right) \quad (16)$$

for a blackbody spectrum, where $f_{\rm X}$ and f_V are the fluxes integrated in the intervals 0.5–2.5 keV and 3000–6000 Å, respectively.

3.2. Beyond the Blackbody Spectrum

The problem of determining the detailed radiation spectrum from accreting NSs was first addressed by Zeldovich & Shakura (1969) and further investigated by Alme & Wilson (1973). Both authors considered a static, plane-parallel, pure H atmosphere with negligible magnetic field, kept hot by the energy released by the infalling protons, and focused on the high accretion rates, typical of X-ray binaries. Models are characterized by two basic parameters: the accretion rate and the penetration depth of protons falling into the NS outer layers. Using the same input physics, Zampieri et al. (1995) extended the calculations to the low-luminosity range ($L \gtrsim 10^{30}$ ergs s^{-1}) relevant to accretion from the ISM. They found that the emerging spectrum is harder with respect to a blackbody at $T_{\rm eff}$. The hardening factor $T_\gamma/T_{\rm eff}$, where T_γ is the radiation temperature, is 2–3 and increases for decreasing luminosity. Not surprisingly, the same behavior is shared by (unmagnetized, H) atmospheres around cooling NSs (Romani 1987). In fact, the hardening is not related to the heat source but to the frequency dependence of the free-free opacity (the most important radiative process). Higher energies decouple in deeper layers, which are hotter, and the final spectrum is, roughly, the superposition of blackbody spectra at different temperatures.

A detailed computation of spectra emerging from strongly magnetized, accretion atmospheres has been recently presented by Zane et al. (2000). Extending previous work (see, e.g., Mészáros 1992 and references therein) they solved the transfer equations in a slab geometry for the two normal modes in the (anisotropic) magnetoactive medium coupled to the hydrostatic and energy balance equations. They have shown that, for $L \sim 10^{30}$–10^{33} ergs s^{-1}, the hard tail present in nonmagnetic models with comparable luminosity is suppressed and the X-ray spectrum, although still harder than a blackbody at $T_{\rm eff}$, is nearly Planckian in shape. At X-ray energies the spectral distribution closely resembles that of a cooling, hydrogen atmosphere with similar properties (see, e.g., Shibanov et al. 1992 and § 7). However, the two models (accreting/cooling) differ rather substantially at optical wavelengths, where the former exhibits a definite excess over the Rayleigh-Jeans tail of the X-ray best-fitting blackbody (see Fig. 2). A more thorough comparison of the

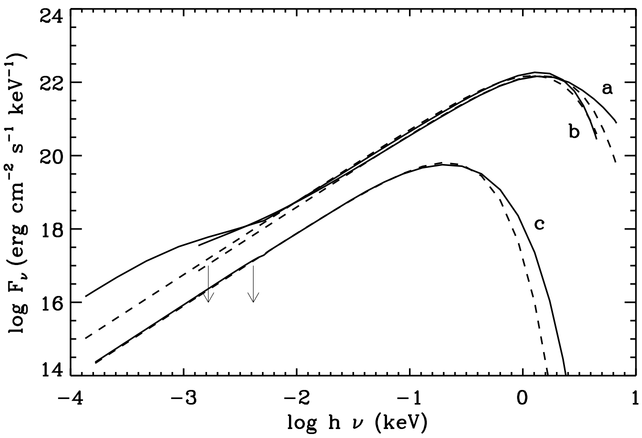

FIG. 2.—Synthetic spectra of pure H accreting (*upper curves*) and cooling (*lower curve*) NSs. (*a*) $B = 0$ G, $L = 4.3 \times 10^{33}$ ergs s^{-1}; (*b*) $B = 10^{12}$ G, $L = 3.7 \times 10^{33}$ ergs s^{-1}; (*c*) $B = 10^{12}$ G, $L = 0.2 \times 10^{33}$ ergs s^{-1}. The blackbody spectra which best fit the X-ray range close to the peak of each spectrum are also shown (*dashed curves*). The two arrows mark the optical band (3000–7500 A).

properties of accreting and cooling models, and of the observational relevance of the optical excess as a signature of accretion, is postponed to § 7.

In concluding this section, we remark that, although this has little effect on the bulk of the emission, for $B \sim 10^{12}$ G the (broad) electron cyclotron line, centered at $\sim 11.6 B_{12}$ keV, becomes a prominent spectral feature over the falling-off Wien continuum, as pointed out by Nelson et al. (1995). The detection of the cyclotron line in conjunction with polarization measures near the proton cyclotron energy (where the degree of polarization crosses zero) may prove a powerful tool in determining the field strength, even in the absence of pulsations (Zane et al. 2000; Pavlov & Zavlin 2000).

4. CONDITIONS AFFECTING THE NUMBER OF ACCRETING ONSs IN THE GALAXY

4.1. The Number of NSs in the Galaxy

The total number of neutron stars in the Galaxy is still uncertain, varying between $N_{\rm tot} \sim 10^8$ and $\sim 10^9$. These figures are inferred from constraints on the nucleosynthetic yields produced in core collapse and from estimates on the present rate of Type II supernova events, as observed in nearby spiral galaxies.

According to Arnett, Schramm, & Truran (1989), core collapse events occur at a rate of one every 10 years and, when averaged over the entire Galaxy lifetime, can account for nearly half of the Galactic Fe abundance. This would imply $\sim 10^9$ NSs if the disk of the Milky Way has a mass of $\sim 10^{11}$ $M_\odot$ and an age of $\sim 10^{10}$ yr. Since thermonuclear events involving the explosion of C/O white dwarfs may contribute to the Fe yield, $N_{\rm tot}$ cannot be determined with higher accuracy.

The present rate of Type II supernova explosions, derived from Cappellaro et al. (1997; see also Madau, Della Valle, & Panagia 1999), is ~ 0.5 h_{50}^2 SNu, where 1 SNu is 1 supernova per 100 yr per 10^{10} $L_{B\odot}$ and h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}. For a Galactic blue luminosity of 5×10^{10} $L_{B\odot}$, this estimate implies a supernova event every 30 years, approximately. Thus, $N_{\rm tot} \sim 3 \times 10^8$ NSs should be present in the Milky Way. However, this estimate may just give a lower limit for $N_{\rm tot}$ since the Galaxy may have experienced phases of enhanced star formation at early epochs. The rate in the past could have been higher by a factor of 10 (Madau et al. 1996), yielding again $N_{\rm tot}$ close to 10^9.

4.2. Space and Velocity Distribution of NSs

The visibility of accreting ONSs is severely constrained by the present velocity distribution, in particular by the extent of a low-velocity tail. As old NSs outnumber young objects, in all likelihood active as pulsars, potential accretors belong predominantly to the dynamically old population which had the time to evolve in the Galactic potential. The velocity distribution of ONSs and their spatial density in the volume accessible to observations can be inferred simulating a large, statistically significant number of orbits in the Galaxy. The strategy followed by a number of authors (BM; Blaes & Rajagopal 1991; Frei, Huang, & Paczyński 1992; Zane et al. 1995) is to start with a seed population, born in the disk with natal kicks determined according to a specific velocity distribution, that evolves dynamically in the Galactic potential. Customarily the distribution of the kick velocity is approximated as isotropic and Gaussian. The neutron star birth rate and spatial distribution mirror those of massive stars in the Galaxy, while pulsars, representative of the parent population, are used to constrain the natal velocity dispersion.

The first to use available velocity information in the statistical analysis of young NSs were Narayan & Ostriker (1990). They found that observations of periods and magnetic fields from a sample of about 300 pulsars are well fitted by invoking the presence of two different populations of NSs at birth: slow (S) and fast (F) rotators. Both have an isotropic Gaussian distribution (relative to the circular speed), the F rotators being characterized by a mean velocity $V_F \sim 60$ km s^{-1} and by a scale height $z_F \sim 150$ pc, much lower than the S ones for which $V_S \sim 240$ km s^{-1} and $z_S = 450$ pc. From this fit, the evolved distribution function of ONSs has been obtained by Blaes & Rajagopal (1991), BM, and Zane et al. (1995). As far as accretion onto ONSs is concerned, only the F population, which represents $\sim 55\%$ of the total number, is relevant. Results from Zane et al.

(1995) show that, after secular evolution, in the local region 7.5 kpc $\leq R \leq$ 9.5 kpc, ONSs are characterized by a mean scale height $\langle z \rangle \sim$ 250 pc and by a mean velocity, averaged over $|z| \leq$ 200 pc, $\langle V \rangle \sim$ 78 km s^{-1}. The number density of NSs, within 2 kpc from the Sun, turns out to be $n_0 \sim 3 \times 10^{-4}(N_{\rm tot}/10^9)$ pc^{-3}.

The previous scenario was challenged by Lyne & Lorimer (1994), who suggested that NSs acquire at birth velocities significantly higher than those of both the F and S subpopulations of Narayan & Ostriker, the imprint of an anisotropic core collapse during a Type II supernova. These authors derived from the observations a typical mean velocity of about 450 km s^{-1}. Recently, on completion of a quantitative analysis, the kinematics of radio pulsars were assessed using population synthesis models and a sample of pulsars with improved statistics and revised distance scale. Yet, the results depicting the true pulsar population are still not unequivocal, due to different criteria used in selecting the sample and in treating observational errors. While Lorimer, Bailes, & Harrison (1997) find a mean natal velocity of 500 km s^{-1}, Hansen & Phinney (1997) claim a lower value, $\sim$250–300 km s^{-1}. Cordes & Chernoff (1998) suggest a possible decomposition of the velocity distribution into two components with mean velocities of 197 and 700 km s^{-1} and fractions 0.84 and 0.16, respectively. Despite these controversies, recent observations seem to point toward an increase in the mean velocity of young NSs relative to Narayan & Ostriker.

Accreting NSs belong necessarily to the low-velocity tail of the population, and at present the low statistics prevent a determination of the extension of such a tail with the required accuracy. Hartman (1997), Hartman et al. (1997), and Iben & Tutukov (1998) do not exclude the presence of a prominent low-velocity component. Dynamical heating (Madau & Blaes 1994) may influence the evolution of slow NSs. This process, observed in the local disk stellar population, causes the velocity dispersion to increase with time as a consequence of scattering by molecular clouds and spiral arms (Wielen 1977). If ONSs participate in the same process, dynamical heating over the lifetime of the Galaxy may scatter a fraction of low-velocity stars to higher speeds, and this, in turn, could devoid the distribution of slow stars.

4.3. The Distribution of the Interstellar Medium

The discussion of the properties of accreting sources, and the study of the detectability of ONSs, require a detailed mapping of the interstellar medium. For a given source, the interstellar density determines both the intrinsic luminosity and the amount of absorption along the line of sight. The situation is more uncertain and complex when dealing with particular regions such as the center of the Galaxy or the solar proximity, while the gas structure is smoother on larger scales and numerical fits to the gas distribution have been published in the literature (see, e.g., Dickey & Lockman 1990 for a detailed review).

In particular, observational data from Lyα and 21 cm absorption measures show that the ISM distribution of both cold and warm H I is nearly constant in radius, while its z-dependence can be fitted by

$$n_{\rm H\,I} = \sum_{i=1}^{2} n_i \exp\left(-\frac{z^2}{2\sigma_i^2}\right) + n_3 \exp\left(-\frac{z}{h}\right), \qquad (17)$$

with $n_1 = 0.395$, $n_2 = 0.107$, $n_3 = 0.064$; $\sigma_1 = 212$, $\sigma_2 = 530$; and $h = 403$ pc; n_i and σ_i are in units of cm^{-3} and pc, respectively. The applicability of the previous expression is restricted to the range $0.4 \leq R/R_0 \leq 1$, where R is the Galactocentric radius and $R_0 = 8.5$ kpc is the distance of the Sun from the Galactic center. The gas layer has a scale height of about 230 pc in the vicinity of the Sun, while for $R \leq 0.4R_0$ it shrinks to $\approx$100 pc and in the outer Galaxy it expands linearly up to $\approx$2 kpc. The other important contribution to the total ISM density comes from molecular hydrogen. The best tracer of H_2 is the CO molecule, and observational data suggest a local Gaussian distribution with a scale height of $\sim$60–75 pc. Observations, however, are much less conclusive as far as the midplane density is concerned (Bloemen 1987), also because it may significantly depend on R (De Boer 1991). As a first approximation, the H_2 distribution can be modeled as a Gaussian with central density 0.6 cm^{-3} and FWHM 70 pc (De Boer 1991). The ionized component gives only a very small contribution to the total density and can be neglected.

The evidence for a complex subparsec structure in the ISM has been recently found by a number of authors on different scales, from 10^4–10^6 AU down to 10–100 AU (see, e.g., Meyer & Lauroesh 1999 and references therein). On all the sampled scales observations imply dense concentrations of atomic gas ($n_{\rm H} \gtrsim 10^3$ cm^{-3}) in otherwise diffuse sight lines. These local condensations cannot be accounted for in the standard McKee & Ostriker (1977) equilibrium pressure model for the ISM, thus further interstellar line mapping is required to increase the small-scale sky coverage and to probe the sophisticated spatial structure. On the other hand, their existence could explain why some ONS candidates are found in very low average density regions.

Even leaving aside the issue of the ISM clumpiness on small scales, the structure of the ISM at distances $\lesssim$1 kpc the ISM is highly anisotropic, and its complex morphology and physical state are currently a very active field of research. At the same time, this represents a particularly favorable site, containing a high number of ONSs that, due to their vicinity, may be relatively easy to detect. Assuming a spatial density of $\sim 3 \times 10^{-4}$ pc^{-3} (§ 4.2; BM; Zane et al. 1995), about 150 ONSs are in fact expected in a sphere of radius 50 pc centered on the Sun. Quite disappointingly, the observability of these close-by NSs as accretion powered sources is severely hindered by the shortage of fuel. In fact, the Sun is surrounded by a region, the Local Bubble, where the plasma has both very low density ($n \sim 0.05$–$0.07\ \mathrm{cm}^{-3}$) and high temperature ($T \gtrsim 10^5$ K). In the scenario proposed by McKee & Ostriker (1977; see also Cox & Anderson 1982; Cox 1983), the hot gas would fill $\sim 70\%$–80% of the interstellar space, and a large number ($\sim 2 \times 10^4$) of cool ($T \sim 80$ K), roughly spherical clouds are expected to be present. Observational data support this model for the region beyond ~ 50–100 pc from the Sun (Knude 1979), but, as discussed by Paresce (1984), soft X-ray, radio, and color excess surveys seem to indicate that no clouds are present at smaller distances and that the denser material is more probably organized into large, elongated, moving fronts within ~ 50 pc. The Sun itself is embedded in a medium, the Local Fluff, which is warm ($T \approx 10^3$–10^4 K) and slightly overdense ($n \sim 0.1\ \mathrm{cm}^{-3}$) with respect to the Local Bubble on scales $\lesssim 20$ pc (Diamond, Jewell, & Ponman 1995).

The present picture indicates that the contour of the Local Bubble in the Galactic plane is highly asymmetric, with four major discontinuities in four different Galactic sectors (Paresce 1984). In particular, a wall of neutral hydrogen is located very close to the Sun in the second quadrant, $15° < l < 120°$. According to Paresce (1984), the wall is roughly parallel to the $l = 330°$–$150°$ axis and is located at $d \leq 16$ pc, with an estimated depth of about 35 pc. The $N_{\mathrm{H\,I}}$ contours presented by Frisch & York (1983) are generally farther away, with the denser material ($n \sim 1\ \mathrm{cm}^{-3}$) at ~ 90 pc from the Sun. Welsh et al. (1994) have derived a highly asymmetric contour of the Local Bubble that in the second quadrant is roughly intermediate between those presented by Paresce and Frisch & York. The minimum radius of the local cavity has been estimated to be ~ 25–30 pc, but, as stressed by the same authors, their indirect method could produce an underestimate of $N_{\mathrm{H\,I}}$ at distances smaller than 50 pc. An analysis of *ROSAT* EUV data (Diamond et al. 1995) has shown that n reaches $\sim 1\ \mathrm{cm}^{-3}$ at ~ 25–30 pc, and this result seems to be in agreement with the asymmetric contour found by Welsh et al. more than with those of Paresce, Frisch, & York (see also Pounds et al. 1993).

5. ARE ONSs DETECTABLE?

As we have seen in the previous sections, the expected luminosity from an ONS accreting from the ISM is $\lesssim 10^{31}$ ergs s^{-1} with a mean photon energy in the interval ≈ 0.1–1 keV. The expected flux at Earth is $\lesssim 10^{-11}(d/100\ \mathrm{pc})^{-2}$ ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (where d is the distance), which translates into $\lesssim 1$ *ROSAT* PSPC counts s^{-1}, well above the typical threshold of the *ROSAT* All-Sky Survey (RASS; ~ 0.02 counts s^{-1}). The sensitivity of the *ROSAT* PSPC, together with its unprecedented capability in the soft X-ray band (~ 0.1–2 keV) put accreting ONSs within observational reach. At the same time the *ROSAT* HRI had a very high angular resolution, which is decisive for follow-up pointed multiwavelength observations of detected sources.

5.1. Selection Criteria for Isolated NSs

Since accreting ONSs should be detectable with *ROSAT*, it is important to establish the most relevant selection criteria. The basic ones, mostly independent of details about the spectral shape, were already proposed by TC:

1. The X-ray–to–optical flux ratio should be extreme (see § 3.1), and the source should show no emission in other energy bands (radio, IR, γ-rays).
2. The X-ray spectrum should be thermal and soft, with typical temperatures $T \approx 100$ eV (see § 3.1).
3. The source must be weak, $L \lesssim 10^{31}$ ergs s^{-1}.
4. The low luminosity makes only close-by sources ($d \approx 100$ pc) potentially detectable. This, in turn, implies that the column density N_{H} must be $\lesssim 10^{21}\ \mathrm{cm}^{-2}$.
5. Since $\dot{M} \propto n$, the spatial distribution of sources should correlate with the denser regions of the ISM.

For close-by sources the visual magnitude should be ~ 25–26, and this might make both the proper motion and the parallax measurable, especially if isolated NSs are fast objects. If the velocity distribution were rich in slow stars, then more distant sources, which may appear in deep exposures, must concentrate along the Galactic plane, because the scale height of both gas and ONSs is ~ 200–300 pc.

5.2. Number of Detectable Sources with *ROSAT*

The observed count rate for a source of monochromatic luminosity L_ν is given by

$$\mathrm{CR} = \int_0^\infty \frac{L_\nu}{4\pi d^2} \exp -(\sigma_\nu N_{\mathrm{H}}) A_\nu \frac{d\nu}{h\nu}\ \mathrm{counts\ s^{-1}}\ , \qquad (18)$$

where σ_ν is the interstellar absorption cross section and A_ν is the detector effective area. If CR represents the detector sensitivity limit, the previous expression can be used to find the maximum distance, d_{max}, at which a star of given luminosity L produces a count rate above the threshold. The total number of detectable ONSs in a given field is obtained by integrating the NS distribution function, $f(r, l, b, v)$, over the solid angle subtending the field and out to d_{max}:

$$N = \int dv \int_\Omega d\Omega \int_0^{d_{\mathrm{max}}} f(r, l, b, v) dr\ , \qquad (19)$$

where l, b are the usual Galactic coordinates.

Using the distribution function of Paczyński (1990), TC concluded that $\sim 6000 N_9$ sources, located within 500 pc, should appear in the RASS. They assumed polar cap accretion ($B = 10^9$ G) and a blackbody spectrum and considered a low value for the uniform ISM density ($n = 0.07$ cm^{-3}), appropriate to the Local Bubble. A more thorough investigation of ONS detectability has been presented by BM. They followed the evolution of the population by integrating the orbits of 10^5 stars moving in the Galactic potential over the Galaxy lifetime. Newly born NSs were assumed to belong to the F subpopulation of Narayan & Ostriker (1990). In the solar proximity the present ONS mean velocity was found to be ~ 80 km s^{-1} and the fraction of stars with $V \lesssim 40$ km s^{-1} $\sim 20\%$, 2 times lower than what is assumed by TC. Their results were, nevertheless, in substantial agreement with those of TC and predicted that several thousand sources should be present in PSPC exposures. Results by BM were improved by Manning, Jeffries, & Willmore (1996), who computed the number of possible detections in the *ROSAT* Wide Field Camera survey with a Monte Carlo simulation. By taking into account effects of a varying magnetic field, NS mass, and exposure times during the survey, they were able to predict a significant depletion in the predicted numbers of detections if the magnetic field has not decayed to values $\lesssim 10^{10}$ G.

Relatively high count rates are expected from ONSs accreting in the denser regions closer to the Sun. Of course, these regions must be large enough to contain a statistically significant number of slow NSs, which are the most luminous. In this respect, dense molecular clouds, where the ambient density is ~ 100 times higher than the average, provide a very favorable environment for observing ONSs. Estimates by BM, Colpi et al. (1993), and Zane et al. (1995), using different assumptions about the emitted spectrum, indicated that the closer clouds should harbor some relatively luminous sources. A detailed analysis of the observability of ONSs accreting in the closest overdense regions of the solar neighborhood has been presented by Zane et al. (1996a). As they pointed out, although the local interstellar medium is underdense and relatively hot, it contains at least one region, the Wall, in which the gas density is ~ 1 cm^{-3}. The Wall extends between ~ 20 and ~ 50 pc, and its angular size is ~ 6000 deg^2. According to these authors, about 10 ONSs are expected to be detectable in the Wall directions, and, due to their vicinity, these sources should appear at the relatively high flux limit of 0.1 counts s^{-1} in the PSPC survey.

Besides the detectability of individual sources, ONSs could also reveal themselves through their contribution to the diffuse X-ray background. This point, originally suggested by ORS, was addressed by BM, who found that the integrated flux above 0.5 keV is negligible under the hypothesis of blackbody emission. Zane et al. (1995) have readdressed this issue, considering polar cap emission and using synthetic spectra, and concluded that magnetized, accreting ONSs can contribute up to $\sim 20\%$ of the unresolved soft X-ray excess observed at high latitudes in the X-ray background (see also De Paolis & Ingrosso 1997 for a discussion of the possible contribution from NSs in the Galactic halo).

Since the diffuse emissivity of accreting ONSs depends on their spatial concentration and on the density of the ISM, the Galactic center (GC), where both the star and gas density are very high, could provide an excellent site for revealing ONS emission. The GC is a well-known source of diffuse emission, investigated by many missions and in particular by *Granat*. ART-P data in the 2.5–30 keV band (Sunyaev, Markevitch, & Pavlinsky 1993; Markevitch, Sunyaev, & Pavlinsky 1993) show the presence of an elliptical diffuse source with different properties below and above ~ 8 keV. Assuming that ONSs represent $\sim 1\%$ of stars in the GC and that their distribution in both physical and velocity space follows that of low-mass stars, Zane et al. (1996b) were able to reproduce satisfactorily the *Granat* data at the lower energies.

6. *ROSAT* RESULTS: THE CRUDE REALITY OF OBSERVATIONS

The search for old, isolated NSs in *ROSAT* images is a by-product of "complete" surveys. Typically one defines a flux threshold and lists all sources which are brighter than that. The threshold should be such that the probability of confusion with the background noise is small. The second step is the search for an optical counterpart on the basis of positional coincidence and peculiar colors. Possible optical candidates are then studied spectroscopically to see if the source belongs to one of the known classes of X-ray emitters. All sources for which no viable optical counterpart was found are classified as NOIDs (non–optically identified objects). Isolated NSs candidates, for which no counterpart is expected down to a visual magnitude ~ 26, must be looked for among NOIDs.

Generally NOIDs are further studied by reducing their X-ray error box. The lack of obvious counterparts in archival optical images, such as the Palomar Observatory Sky Survey, is used to set a lower limit on the X-ray–to–optical flux ratio. Sources with $f_X/f_V \gtrsim 1000$ are classified as potential isolated NS candidates. Obviously, the number of NOIDs in a given region is an absolute upper limit on the number of ONSs.

RASS and deep-field exposures of the most favorable sites (such as giant molecular clouds) have been searched for accreting ONSs, and, although the various surveys were conducted with rather inhomogeneous criteria, an important result soon became apparent. The upper limits on ONS candidates were substantially below expectations by, at least, 1 order of magnitude. Results from the surveys are reviewed in § 6.5, and the implications of this (negative) conclusion are examined in § 8.

Despite ONSs being much more elusive than originally expected, the observational efforts of the last few years have produced some promising candidates and their number keeps increasing: one in 1995, two in 1996, one in 1998, and three in 1999. All of them were discovered, or rediscovered, as in the case of MS 0317.7−6647 and RX J185635−3754, with *ROSAT*, both serendipitously and in survey data (mainly the *ROSAT* Bright Survey [RBS]). The main properties of the seven candidates discovered so far are reviewed in the following subsections and summarized in Table 1.

Although present observations leave little doubt that these sources are associated with isolated NSs, the exact nature of the mechanism powering their emission is still controversial: either accretion of the ISM onto old neutron stars or thermal radiation from middle-aged, cooling NSs. As we discuss in § 7, the emission properties of these two classes of objects are rather similar, and the present data cannot provide convincing evidence in favor of either possibility.

6.1. MS 0317.7−6647

This source was the first to be proposed as an accreting ONS, and, although its association with a neutron star was never supported by further observations both in X-rays and in the optical, we include it in our list.

MS 0317.7−6647 was already present in the *Einstein* Medium Sensitivity Survey (Gioia et al. 1990) and then reobserved with *ROSAT* by Stocke et al. (1995). It is a soft, very weak ($\sim$0.03 counts s^{-1}) source in the field of the nearby galaxy NGC 1313. From the three available X-ray images there is evidence that this source is variable over the timescale of years. The only possible optical counterpart has $m_V = 20.8$, which brings the X-ray–to–optical flux ratio to $f_X/f_V \gtrsim 60$. The simultaneous lack of radio emission seems to rule out the possibility of an extreme BL Lac object, leaving only a compact object as a reasonable option. Identifying the source with an X-ray binary in NGC 1313 leads to a luminosity $L \sim 10^{40}$ ergs s^{-1} and requires a mass of the compact object $\sim 50\ M_\odot$. Such a large value for the black hole mass, and the high Galactic latitude of the source, which makes it unlikely to be an X-ray binary in our own galaxy, were taken as clues in favor of the isolated NS option. The PSPC spectrum, which is well fitted by a blackbody with $T \sim 200$ eV, and the derived luminosity, $L \sim 1.7 \times 10^{30}$ ergs s^{-1} placing the object at 100 pc, are fully compatible with those of an isolated, nearby neutron star. The presence of a galactic IR cirrus cloud in the field of view of the source supports this possibility, while the sign of variability argues against the hypothesis of a cooling neutron star (Brazier & Johnston 1999).

6.2. RX J185635−3754

RX J185635−3754 is a rather bright source, already present in the *Einstein* slew survey and observed with *ROSAT* by Walter et al. (1996). The PSPC count rate, $\sim$3.6 counts s^{-1}, corresponds to an X-ray luminosity $L \sim 5 \times 10^{31}$ ergs s^{-1} for a distance of 100 pc. The observed spectrum is very soft, and the best fit with a blackbody gives a temperature of about 60 eV. The original claim that this source is an isolated neutron star was supported by the absence of an optical counterpart down to $m_V \sim 23$, giving $f_X/f_V > 7000$.

Further X-ray and optical observations were performed by Neuhäuser et al. (1997) and Campana, Mereghetti, & Sidoli (1997) in an attempt to identify the optical counterpart and to assess its distance. The source appears projected against the molecular cloud R CrA and the column density

TABLE 1

ISOLATED NS CANDIDATES

Source	PSPC (counts s^{-1})	T_{bb} (eV)	N_H (10^{20} cm^{-2})	log f_X/f_V	Period (s)	References
MS 0317…….	0.03	200	40	>1.8	…	1
RX J1856……	3.64	57	2	4.9	…	2, 3, 4, 5
RX J0720……	1.69	79	1.3	5.3	8.37	6, 7, 8
RBS 1223……	0.29	118	~1	>4.1	…	9
RBS 1556……	0.88	100	<1	>3.5	…	9, 10
RX J0806……	0.38	78	2.5	>3.4	…	11
RX J0420……	0.11	57	1.7	>3.3	22.7	12

REFERENCES.—(1) Stocke et al. 1995; (2) Walter et al. 1996; (3) Neuhäuser et al. 1997; (4) Campana et al. 1997; (5) Walter & Matthews 1997; (6) Haberl et al. 1997; (7) Motch & Haberl 1998; (8) Kulkarni & van Kerkwijk 1998; (9) Schwope et al. 1999; (10) Motch et al. 1999; (11) Haberl et al. 1998; (12) Haberl et al. 1999.

derived from X-ray data ($N_H \sim 2 \times 10^{20}$ cm^{-2}) is less than that in the cloud itself. The cloud is estimated to be $\sim$120 pc away, so the source is likely to be closer. X-ray spectral fits with more sophisticated models of cooling and accreting NS atmospheres were presented by Pavlov, Stringfellow, & Córdova (1996) and Campana et al. (1997). Unmagnetized cooling spectra with different chemical compositions predict an optical flux that is either too large or too small, while both magnetized cooling and unmagnetized accreting hydrogen models are consistent with the data only if the source is as close as $\sim$10 pc, and this seems difficult to reconcile with the derived values of the column density.

The real nature of RX J185635−3754 became even more puzzling when Walter & Matthews (1997) reported the discovery of a possible optical counterpart with the *Hubble Space Telescope*. Their candidate, selected on the basis of positional coincidence and its blue color, is a faint, stellar-like object with $m_V \sim 25.6$, giving an X-ray–to–optical flux ratio $\sim$75,000. They determined the optical flux at two wavelengths, $\lambda = 3000$ and 6060 Å, and both points lie above the Rayleigh-Jeans part of the blackbody spectrum which best fits the X-rays. The presence of a definite optical excess, about a factor of 3, points toward a more complex spectrum and no definite explanation for this has been found up to now (see § 7 for details).

6.3. RX J0720.4−3125 and RX J0420.0−5022

RX J0720.4−3125 was observed for the first time with *ROSAT* by Haberl et al. (1996, 1997). The source was detected with the PSPC at a level of $\sim$1.7 counts s^{-1}, and the soft spectrum is well fitted by a blackbody at $T \sim 80$ eV. The column density derived from the fit is low, $N_H \sim 10^{20}$ cm^{-2}, placing the source at a relatively close distance, $d \approx 100$ pc, with a luminosity $L \sim 2.6 \times 10^{31}(d/100\ \mathrm{pc})^2$ ergs s^{-1}. Preliminary optical searches produced a limiting magnitude for the counterpart of $m_V > 21$, implying a flux ratio greater than 500.

Although the X-ray properties make RX J0720.4−3125 and RX J185635−3754 quite similar, RX J0720.4−3125 has been found to pulsate in X-rays, with a period $P = 8.39$ s. If indeed this source is powered by accretion, the knowledge of the luminosity and of the period allows an estimate of the magnetic field strength, as already pointed out by Haberl et al. (1997). The condition that the corotation radius is larger than the Alfvén radius (see eq. [8]) implies $B \lesssim 10^{10}$ G, indicating a substantial decay of the magnetic field in this object.

Haberl et al. (1997) suggested that such values of B and P may be the result of common envelope evolution in a high-mass X-ray binary. In this case the history of RX J0720.4−3125 would bear resemblance to that of the anomalous X-ray pulsars (AXPs; Mereghetti & Stella 1995) if the last are interpreted as accreting from a residual circumstellar disk (van Paradijs, Taam, & van den Heuvel 1995). Their observed periods, in the 5–10 s range, are surprisingly similar to that of RX J0720.4−3125. Konenkov & Popov (1997) and Wang (1997; see also Colpi et al. 1998) have shown that the present position of RX J0720.4−3125 in the *B-P* plane is consistent with the long-term evolution ($\sim 10^9 - 10^{10}$ yr) of a slow ($\sim$20 km s^{-1}) NS, born with canonical values of the magnetic field and period, which experienced field decay over a timescale $\gtrsim 10^8$ yr. The two evolutionary scenarios (common envelope or spontaneous decay) will lead to the same kind of object, i.e., a slow, accreting NS, but on quite different timescales, $\lesssim 10^7$ versus 10^9–10^{10} yr.

An alternative explanation to the observed properties of RX J0720.4−3125 was recently proposed by Heyl & Kulkarni (1998; see also Wang 1997 and Heyl & Hernquist 1998). In this picture the source is powered by the release of internal energy, a magnetar kept hot by magnetic field decay. For $B \sim 10^{14}$ G, the time required to cool down the NS to the observed temperature is $\sim 10^5$ yr, so contrary to the accretion scenario, RX J0720.4−3125 should contain a young NS with a decaying field. Heyl & Kulkarni argued that the source could be the descendant of an anomalous X-ray pulsar. In this interpretation, AXPs are a class of isolated neutron stars with unusually high magnetic fields, powered by its decay (Thompson & Duncan 1996; see also Colpi, Geppert, & Page 2000).

Recent follow-up optical observations (Motch & Haberl 1998; Kulkarni & van Kerkwijk 1998) led to the identification of a possible optical counterpart, a faint, bluish object with $m_B \sim 26.6$. Again the identification is based on positional coincidence and color and gives $f_X/f_V \sim 2 \times 10^5$. The observed optical flux, similar to that of RX J185635−3754, exceeds that predicted by the blackbody spectrum which fits the *ROSAT* data by a factor $\sim$5 (Kulkarni & van Kerkwijk 1998).

RX J0420.0−5022 is the last isolated NS candidate discovered so far and the only one, together with RX J0720, to exhibit a modulation in the X-ray flux with a period $\sim$22.7 s (Haberl et al. 1999). It has the lowest observed count rate ($\sim$0.11 PSPC counts s^{-1}) but shows all the distinctive features common to other sources in this class: a thermal spectrum with $T \sim 57$ eV and $N_H \sim 2 \times 10^{20}$ cm^{-2}, which give $L \sim 2.7 \times 10^{30}(d/100\mathrm{pc})^2$ ergs s^{-1}. New Technology Telescope optical observations revealed no unusual object in the X-ray error box down to a magnitude $m_B \sim 25$, implying an X-ray–to–optical flux ratio larger than $\sim$20,000.

6.4. RBS 1223, RBS 1556 (RX J1605.3+3249), and RX J0806.4−4132

RBS 1223 and RBS 1556 are two rather bright sources, $\sim$0.3 and $\sim$0.9 PSPC counts s^{-1}, respectively, detected in the RBS and then observed in follow-up pointings by

Schwope et al. (1999) and Motch et al. (1999). Both sources have similar properties, a thermal X-ray spectrum with little absorption ($T \sim 100$ eV, $N_{\rm H} \sim 10^{20}$ cm^{-2}). Optical images taken at Keck show no possible optical counterpart down to $m_B \sim 26$ for RBS 1223 (Schwope et al. 1999) and to $m_V \sim 24.2$ for RBS 1556 (Motch et al. 1999), giving a lower limit for the X-ray–to–optical flux ratio in excess of 10,000.

RX J0806.4−4132 has been serendipitously discovered by Haberl et al. (1998) in archival PSPC observations of a candidate supernova remnant. The quite large angular distance from the source makes a physical association unlikely. The source has all the distinctive features of the other candidates, the spectrum is thermal with $T \sim 80$ eV and the column density is low, $N_{\rm H} \sim 2.5 \times 10^{20}$ cm^{-2}. Preliminary optical searches revealed no unusual object in the X-ray error box down to a blue magnitude ~ 24.

6.5. Results from *ROSAT* Surveys

Belloni et al. (1997) have performed a systematic search for ONSs in two molecular clouds in Cygnus, the Rift and OB 7, by analyzing archive *ROSAT* PSPC pointings; this is the only deep-field survey available up to now. Observations cover only a small fraction of the clouds, $\sim 5\%$, and contain 109 sources above a flux limit of ~ 0.0015 counts s^{-1}. For 105 of them an optical counterpart was identified, leaving four NOIDs, with no counterpart above $m_R \sim 20$. Although presently inferred values of $f_{\rm X}/f_V \sim 1$ are not large enough to qualify these sources as strong ONS candidates, their positional coincidence with dense clouds together with their hardness ratio $\gtrsim 0.3$ make them worthy of future investigations. Belloni, Zampieri, & Campana estimated the number of detectable ONSs in the searched area following the criteria of § 5.1 and found that it exceeds the number of NOIDs by a factor of 3–10. Since ONSs can account only for a fraction of NOIDs, this results provides a clear indication that theoretical figures produced so far overestimated the actual number of detectable sources. A similar conclusion follows from the comparison between the predicted number of resolved sources, ~ 10 deg^{-2}, and that of NOIDs in high-latitude PSPC pointings, ~ 30 deg^{-2}, discussed by Zane et al. (1995) in connection with the possible contribution of ONSs to the diffuse X-ray background. As they noted, this would imply that one NOID in three should be an ONS.

A more complete analysis of a larger sample region in Cygnus, ~ 64.5 deg^2, comprising a large part of the cloud OB 7, by Motch et al. (1997) using RASS data lends further support to this idea. The survey is complete to about 0.02 counts s^{-1}, and, at this flux level, 68 sources are detected. Catalog searches and optical follow-up observations have shown that the vast majority of these sources are associated with active coronae (F–K and M stars). There are eight NOIDs, and they do not seem to be correlated with the denser regions of the cloud. Again this figure is lower than the estimated number of ONSs emitting above 0.02 counts s^{-1} (~ 10 according to Zane et al. 1995).

A definite confirmation of the paucity of detectable ONSs in *ROSAT* images came from the work of Danner (1998a, 1998b). He searched both high-latitude molecular clouds and dark clouds in the Galactic plane for soft, thermal X-ray sources using RASS data. The high-latitude cloud sample used by Danner is that originally investigated by Magnani, Blitz, & Mundy (1985), and the searched area is ≈ 125 deg^2, substantially larger than that occupied by the clouds themselves, ~ 64.5 deg^2. The total number of sources within the cloud boundaries is 89 and the survey should be complete to 0.012 counts s^{-1}. Of the 89 sources, 54 are firmly identified with active galactic nuclei or stars, while for those remaining one, or more, plausible counterparts are reported. The claim is that at most one source could have escaped the identification program, so the derived upper limit on the projected density of ONSs is ~ 0.016 deg^{-2}. This figure is smaller than the number expected, ≈ 0.15 deg^{-2} according to Zane et al. (1995), by at least 1 order of magnitude. In his dark cloud sample, which coincides with that analyzed by Zane et al. (1995), only 16 sources met the selection criteria and all of them have a firm, or at least plausible, optical counterpart, in most cases a bright star. The only exception is RX J1856.6−3754, but no other source with similar properties was found. Since the dark cloud sample covers an area of ~ 1600 deg^2 and only one isolated NS candidate is detected, the ONS projected density is $\lesssim 6 \times 10^{-4}$ deg^{-2} at a count rate of 0.05 counts s^{-1}. A direct scaling of the results in Table 5 of Zane et al. (1995) to a fixed (i.e., independent of the cloud) threshold of 0.05 counts s^{-1} gives 50 detectable sources in the same area, nearly 2 orders of magnitude in excess of the observed upper limit.

7. ACCRETING VERSUS COOLING NEUTRON STARS

According to the canonical scenario, soon after it is born in a Type II supernova event, a NS is very hot ($T \sim 10^{11}$ K), has large magnetic field ($B \gtrsim 10^{12}$ G), and has a short period ($P \sim 0.01$ s). However, neutrino emission quickly brings the temperature down to $\sim 10^{6.5}$–10^6 K in about 10^3–10^4 yr (see, e.g., Page 1998). For the next $\sim 10^5$ yr, the star temperature stays roughly constant (at $\lesssim 10^6$ K) and the NS can be observed also in the X-ray band as a weak, soft, thermal source. X-ray emission from radio pulsars and from the γ-ray pulsar Geminga has been convincingly observed (see, e.g., Ögelman 1991, 1995; Foster, Edelstein, & Bowyer 1996; Bignami & Caraveo 1996 for reviews; see also Becker & Trümper 1998). Many of these sources show a two-component spectrum, and, while the origin of the hard, nonthermal component remains uncertain, the soft component almost certainly originates from the NS surface. Fitting this thermal component with a blackbody gives $T_{\rm eff} \sim 10^5$–10^6 K, with lower temperatures associated with older pulsars (see, e.g., Pavlov et al. 1995).

Because of the typical values of $T_{\rm eff}$, L, and the thermal spectrum, a middle-aged, radio-quiet, cooling object appears quite similar to an accreting ONS in soft X-rays. This introduces an ambiguity, and the association of the isolated NS candidates discovered so far with either an old or a (relatively) young object remains a matter of lively debate. It is therefore extremely urgent to improve our theoretical understanding of these two classes of sources, looking, in particular, for spectral signatures which can enable us to discriminate between them.

In principle, the lack of pulsations in the X-ray data could be used as an argument against the presence of a high magnetic field. This, in turn, may suggest that the field has decayed, favoring an interpretation in terms of an old NS (see § 8). Unfortunately, this is far from being conclusive since the co-alignment between the rotation axis or the line of sight and the magnetic axis would produce no pulsations even for high B. On the other hand, field decay in isolated objects is highly questionable, so the presence of pulsations is even less conclusive in estimating the age of the NS.

At least one candidate, RX J1605.3+3249 for which X-ray measures cover a substantial time interval, shows a remarkably constant flux on various timescales (weeks to years). Motch et al. (1999) argued that this can be taken as a hint in favor of the cooling picture, because accretion instabilities should lead to X-ray variability on a free-free timescale which is ≈ 1 yr under typical conditions. Also, ISM dishomogeneities on the smallest scales may give rise to variations in the accretion rate. At a velocity of ~ 40 km s^{-1}, an ONS would travel a distance ~ 100 AU in the time separating the first and last *ROSAT* observations of RX J1605.3+3249 (~ 7.5 yr).

The (expected) similarity between accreting (low luminosity) and cooling NSs is not surprising. In both cases models are based on a geometrically thin, static atmosphere in LTE which has roughly the same thermodynamical properties. The only difference is the energy input, either the heat released by the impinging ions or thermal radiation emanating from the NS crust.

The problem of calculating the spectrum emerging from cooling NSs has been widely investigated by a number of authors, both for different chemical compositions and for low and high magnetic fields (see, e.g., Romani 1987; Miller & Neuhäuser 1991; Shibanov et al. 1992; Miller 1992; Pavlov et al. 1994, 1995; Zavlin et al. 1995; Zavlin, Pavlov, & Shibanov 1996; Rajagopal & Romani 1996; Pavlov et al. 1996; Rajagopal, Romani, & Miller 1997). These studies showed that emerging spectra are not too different from a blackbody at the star effective temperature. For $B \lesssim 10^{10}$ G, spectra from pure H atmospheres exhibit a distinctive hard tail that becomes less pronounced when the magnetic field is $\sim 10^{12}$–10^{13} G. However, as already mentioned in § 3.2, this feature cannot be taken as characteristic of a cooling object, since similar conclusions were reached for the spectrum emitted by low-luminosity, low-field, accreting NSs (Zampieri et al. 1995; Zane et al. 2000).

While a cooling atmosphere is likely to be rich in heavy elements which results from the supernova explosion and the subsequent envelope fallback, the assumption of a pure hydrogen composition, although crude, is plausible for an accretion atmosphere. In this case, in fact, incoming protons and spallation by energetic particles in the magnetosphere may enrich the NS surface with light elements (mainly H), and, owing to the rapid sedimentation, these elements should dominate the photospheric layers (Bildsten, Salpeter, & Wasserman 1992). As detailed calculations have shown, the overall emission strongly depends on the chemical composition. This led to the suggestion that the comparison between observed and synthetic X-ray spectra may probe the chemistry of the NS crust and, indirectly, shed light on the powering mechanism.

Additional information on the nature of these sources may come from optical observations. In fact, accretion spectra have been found to exhibit a characteristic excess over the Rayleigh-Jeans tail of the best-fitting (Planckian) X-ray distribution, which is not shared by cooling models with similar parameters (see Fig. 2; Zane et al. 2000). The presence of an optical bump is due to the fact that in the outermost layers the heating produced by accretion cannot be balanced by free-free cooling. The temperature then rises until $T \sim 10^7$–10^8 K, when Compton cooling becomes efficient. The presence of this hot "corona" does not influence the propagation of X-ray photons, which come from the inner layers, but makes the optical photosphere slightly hotter than in the cooling case.

The observation of an optical excess has been reported in the spectrum of RX J18563.5−3754 (see § 6.2). Although the optical identification of RX J0720.4−3125 still lacks a definite confirmation, it is interesting to note that the counterpart proposed by Kulkarni & van Kerkwijk (1998) also shows a similar excess.

The multiwavelength spectrum of RX J18563.5−375 has been the subject of various investigations. Models of cooling atmospheres based on different chemical compositions fail to predict the correct optical fluxes (Pavlov et al. 1996), while models with two blackbody components or with a surface temperature variation may fit the f_{3000} flux. In particular, the fact that a simple model with $T \propto ({\rm latitude})^{0.25}$ and with magnetic and rotational axes co-aligned can match the observed spectral energy distribution (SED) favored the interpretation of RX J18563.5−3754 as a cooling NS (Walter & Matthews 1997). Recent spectra from nonmagnetic atmospheres with Fe or Si-ash compositions (Walter & An 1998) may also provide a fit of both the X-ray and optical data, although they still need a definite confirmation. The magnetized model by Zane et al. (2000) indeed predicts an optical excess of about the right order indicating that, given the considerable latitude of the unknown parameters, the full SED may be consistent with the picture of an accreting NS. However, no detailed fit for RX J185635−3754 has been attempted yet. It should also be noted that accretion spectra, irrespective of details on their shape, are intrinsically harder because of the reduced emitting area (see eq. [15]). Assuming $f \sim 0.01$, which is conservative if the field is high and equation (15) is taken literally, the luminosity corresponding to a peak energy of ~ 100 eV is 10^{28}–10^{29} ergs s^{-1}, more than 1 order of magnitude lower than what follows from observations placing the source at ~ 100 pc.

There has been a preliminary report of a proper motion measurement for RX J185635−3754 by the MPE group (J. Trümper 1999, private communication).[1] If confirmed, the value of $\sim 0''.34$ yr^{-1} would imply a projected velocity of ~ 160 (d/100 pc) km s^{-1}. Such a high velocity is definitely incompatible with the observed flux, if the source is powered by accretion and $d \sim 100$ pc. Nevertheless, the accretion option could still be consistent with the data placing the source at a closer distance. For $d \sim 30$ pc, a velocity ~ 50 km s^{-1} would give both the correct values of the proper motion and the luminosity. Besides, a distance of the same order was derived by Campana et al. (1997) from the fit of *ROSAT* data with the unmagnetized synthetic spectrum of Zampieri et al. (1995). Two major objections still remain. First, the observed column density is too large to be consistent with $d \sim 30$ pc, taking into account that the local ISM is underdense. Second, the probability of finding a NS so close *and* with such a low velocity must be extremely small, also in the light of the recent result by Popov et al. (1999). Here we just mention that, at variance with cooling atmospheres, all accretion spectral models were computed so far under the assumption of complete H ionization and do not include the contribution of the atmospheric neutral atoms to the column density. A rough estimate shows that a small fraction of neutrals ($\lesssim 10\%$) is anyway expected and this may produce the required absorption "in loco." As far as the second point is concerned, it is worth noting that the chance of finding a slow ONS at 30 pc is not much slimmer than that of seeing a fast, cooling NS at 100 pc. Taking a total number of NSs $\sim 10^9$, the average ONS separation is ~ 15 pc, so the probability of finding it at 30 pc is essentially 1. According to Popov et al. (1999) the fraction of low-velocity NSs is less than 1%. This gives a total probability of $\lesssim 1\%$. Cooling NSs are short-lived, $t_{cool} \sim 10^5$–10^6 yr (Page 1998), and their average separation is larger, ~ 270 pc. Now the probability of finding a cooling NS with $V \sim 240$ km s^{-1} is essentially unity, but the chance of having it inside 100 pc is therefore $\sim (100/270)^3 \sim 0.05$. The conclusion is that *both* events are quite rare.

The problem of distinguishing between accreting and cooling isolated NSs on the basis of a statistical analysis has been recently faced by Neuhäuser & Trümper (1999). They have shown that the log N–log S curve for the observed candidates is closer to that of coolers, at least if ONSs are taken as a slow population as in TC and BM, and suggested that higher mean velocities may yield better agreement with observed upper limits. This particular point will be addressed in § 8.2.

[1] See also F. Walter's home page (http://sbast3.ess.sunysb.edu/fwalter/plan.html).

8. WHY ARE SO FEW NSs DETECTED?

As discussed in § 7, the first analyses of *ROSAT* survey data are mainly negative as far as ONSs are concerned, leading to a problem of paucity of detections. The theoretical predictions of the "pre-*ROSAT*" epoch appeared to be quite optimistic, forcing theoreticians to reconsider critically their starting assumptions. While the ONS spectral properties are rather well established, earlier statistical estimates rely on a number of crucial assumptions concerning the velocity distribution of pulsars at birth and the long-term evolution of the magnetic field. Previous studies (see § 5.2) were based on the hypothesis that nearly all ONSs have a residual magnetic field $\sim 10^9$ G and are presently in the accretor phase. However, accretion is just one of the different phases that an NS can experience. Normally born in the ejector stage, the NS later enters the propeller phase and the accretor phase if the conditions are favorable. A time-dependent magnetic field may therefore change the duration of these phases and alter the statistics of visible ONSs. The evolution of the B field in isolated NSs is still a very controversial issue. Little evidence comes from the pulsar statistics, and one should rely only on theoretical models (see, e.g., Srinivasan 1997). Theoretical results are far from being unequivocal and predict either exponential/power-law field decay (Ostriker & Gunn 1969; Sang & Chanmugam 1987; Urpin, Chanmugam, & Sang 1994; Miri 1996; Urpin & Muslimov 1992; Urpin & Konenkov 1997) or little or no decay at all within the age of the Galaxy (Romani 1990; Srinivasan et al. 1990; Goldreich & Reisenegger 1992; see also Lamb 1992 for a review). Statistical analyses based on observations of isolated radio pulsars are consistent with no field decay over the pulsar lifetime (Narayan & Ostriker 1990; Sang & Chanmugam 1990; Bhattacharya et al. 1992). However, this does not preclude the possibility of field decay over longer timescales. Different approaches to pulsar statistics led, independently, to the conclusion that, if the magnetic field decays, then it probably does so over a timescale $\sim$100 Myr (Hartman et al. 1997).

A step forward in the statistical analysis is therefore to assume different laws for the time evolution of the field and to combine the dynamical evolution of the simulated population with its magnetorotational evolution. This has been computed for the first time by Popov et al. (1999) and is discussed in § 8.2. In § 8.1, we briefly summarize the role played by the magnetic field in affecting the NS magnetorotational evolution.

It should also be mentioned that the Bondi-Hoyle accretion rate (eq. [10]) may be just an upper limit. As discussed by Blaes, Warren, & Madau (1995) the EUV–X-radiation released in the accretion process can heat the surrounding medium, producing an increase of the sound speed which, in turn, tends to decrease $\dot{M}$. This effect, known as *preheating*, may severely reduce the accretion rate in ONSs.

8.1. The Role of the Magnetic Field

The permanence of an NS in the ejector (or propeller) phase depends on the magnetic field strength and is influenced by its time evolution. Livio et al. (1998) and Colpi et al. (1998) were the first to recognize that an NS can straggle in the ejector or propeller state for a time longer than the present cosmic time mainly as a consequence of magnetic field decay. This may cause the paucity of accreting ONSs. On a theoretical basis, the decay occurs either because of ohmic dissipation of crustal currents sustaining the field (Sang & Chanmugam 1987; Urpin & Konenkov 1997) or because of the migration of the proton fluxoids from the core to the crust due to continuous spin-down (Srinivasan et al. 1990).

The idea that an NS may never become an accretor is rather simple and can be illustrated by just estimating the duration of the ejector stage τ_E and introducing a simple exponential decay law for the field. Magnetic dipole braking in this phase keeps the neutron star spinning down at a rate

$$\dot{P}_{\rm dipole} \sim 10^{-8}\left[\frac{B(t)}{10^{12}\ {\rm G}}\right]^2 P^{-1}\ {\rm s\ yr}^{-1} \qquad (20)$$

until $P_{\rm crit}$ is reached (see eq. [6]). The critical period is itself a function of time ($P_{\rm crit} \propto B^{1/2}$) and decreases as $B(t)$ decays. Two competing effects thus come into play: (i) the spin-down rate slows down because of the weakening of the field, causing the NS to stay longer in the ejector state; (ii) $P_{\rm crit}$ decreases with time and this acts in the opposite way, making τ_E shorter. If the field decays exponentially on a scale τ_d from its initial value B_0 down to a minimum value B_b (the presence of a relic field is mainly suggested by the stability of the field in millisecond pulsars), then the duration of the ejector stage can be computed analytically. Following closely Popov & Prokhorov (1999), the ejector timescale is

$$\tau_E = \begin{cases} -\tau_d \ln\left[\dfrac{\tau_0}{\tau_d}\left(1+\dfrac{\tau_d^2}{\tau_0^2}\right)^{1/2} - 1\right] & \tau_E < \tau_b\,, \\ \tau_b + \dfrac{B_0}{B_b}\left[\tau_0 - \dfrac{1}{2}\,\tau_d(1-e^{2\tau_b/\tau_d})\right] & \tau_E > \tau_b\,, \end{cases} \qquad (21)$$

where $\tau_b = \tau_d \ln(B_0/B_b)$ is the time at which the NS reaches the minimum field and

$$\tau_0 \sim 4n^{-1/2} v_{40} (B_0/10^{12} {\rm G})^{-1}\ {\rm Gyr} \qquad (22)$$

is the duration of the ejector phase for a constant field; note that τ_0 depends on v and n. Figure 3 shows the loci where the time spent in the ejector phase equals the age of the Galaxy, $\tau_E = 10$ Gyr, as a function of the minimum field and of the decay timescale. Different curves refer to initial fields of 5×10^{11}, 10^{12}, and 2×10^{12} G and $v = 40\ {\rm km\ s^{-1}}$, $n = 1\ {\rm cm^{-3}}$ were assumed. The "forbidden" region, where $\tau_E > 10$ Gyr, lies below each curve. As is apparent from Figure 3, the parameter range for which the NS never leaves the ejector stage is significant even for the rather low value of the star velocity we adopted. It is interesting to note that unhalted decay (i.e., $B_b \to 0$) would drive all NSs into the accretor phase, since the Alfvén radius becomes smaller than the star radius as the field decays.

Colpi et al. (1998) considered a model in which the spin evolution causes the core field to migrate to the crust where dissipation processes drive ohmic field decay. They found that for a characteristic timescale of $\sim 10^8$ yr (a value consistent with the limits on the decay timescale inferred from

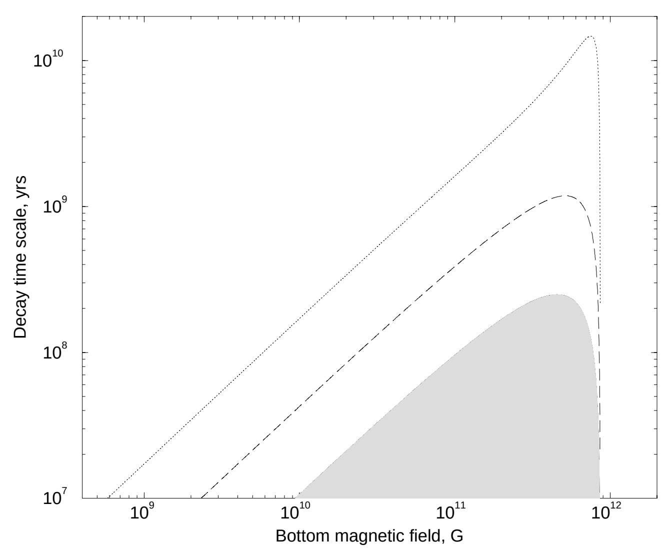

FIG. 3.—Loci where the ejector lifetime equals the age of the Galaxy (see text for details).

pulsar statistics) the number of ONSs that are at present in the accretion stage can be reduced by a factor of 5 over previous figures. Most of the (low velocity) ONSs would now be in the ejector or the propeller stages.

8.2. Are ONSs Fast?

Pulsars have large kick velocities. Thus, if NSs at birth acquire large mean speeds, their distribution may be devoided of low-velocity stars. This may explain the paucity of observed ONSs. In the light of new data on pulsars (see § 4.2) a reanalysis of the statistical properties of NSs is required.

Popov et al. (1999) studied the effect of an increasing initial mean velocity on the visibility of ONSs. In this investigation, the NS spin-down induced by dipole losses and their interaction with the ambient medium (described using a realistic map of the ISM in the Galaxy) have been followed, together with their dynamical evolution in the Galactic potential, in unprecedented detail. Not unexpectedly, the ejectors were found to outnumber the accretors (and the propellers): they comprise more than 95% of all NSs at $\langle V \rangle \sim 150$ km s^{-1}. The visible ONSs fall off rapidly when $\langle V \rangle$ is above 200 km s^{-1}, owing to the lack of low-velocity stars with increasing mean speed.

Using the present upper limits on the number of detected ONSs, Popov et al. (1999) were able to constrain the pulsar velocity distribution independently of radio observations. Taking a (generous) upper limit of 10 accreting sources within 140 pc from the Sun, these authors inferred a lower bound on the mean kick velocity $\langle V \rangle$ of 200–300 km s^{-1}, corresponding to a dispersion $\sigma_V \sim 125$–190 km s^{-1}, in agreement with the findings of Cordes & Chernoff (1998). In addition, these results have been able to constrain the fraction of pulsars in the low-velocity tail which could have escaped pulsar statistics, to less than 0.05%.

9. CONCLUSIONS

In the last decade old neutron stars accreting from the interstellar medium have been actively sought, mainly in X-ray *ROSAT* images. Although the quest produced half a dozen strong candidates, none of these can be unambigously claimed as an accreting, isolated NS, so that the very existence of this class of sources is not observationally proved as yet.

The expected number of observed ONSs depends on the physical properties of their progenitors, young NSs in the pulsar phase. The key quantities are their velocity distribution and the law of magnetic field decay, both subjects being frontline problems in pulsars physics. Pulsars and ONSs would be the alpha and omega of the evolution, which brings the neutron star through the intermediate phases of ejector and propeller.

The physics of propellers is poorly known, and, especially in the case of very low accretion rates, it is suspected that emission could be nonstationary. If flaring episodes do occur, they may be of critical importance in recognizing a population, which is otherwise inaccessible because of its intrinsic low luminosity.

Substantial improvements of our current understanding of the isolated NS candidates discovered so far are expected from next-generation X-ray satellites. Advanced spectroscopy with *Chandra*, *XMM*, and *Astro-E* will provide high-resolution X-ray data which can reveal many properties of the NS atmosphere, such composition, gravitational redshift, and temperature. The comparison of high-quality spectra with models might indeed prove decisive in assessing the nature of these sources. Optical observations with the largest telescopes, already operational, like Keck and the Very Large Telescope, would prove to be of the same importance in solving the riddle of isolated NS candidates. Without the identification of optical counterparts, they will remain X-ray–bright NOIDs. High-quality spectroscopy of the optical counterparts is needed to assess better the (possible) deviations from the Rayleigh-Jeans tail of the X-ray spectrum, like those reported in two candidates so far.

Hopefully the next decade will bring us strong new candidates for isolated NSs steadily accreting from the ISM and the discovery of the previous unsteady phase.

We would like to express our gratitude to a number of colleagues for many enlightening discussions. In particular we wish to thank Christian Motch, Fred Walter, Phil Charles, Sergio Campana, Sandro Mereghetti, Sergei Popov, and Luca Zampieri for their helpful suggestions on the manuscript. This work has been partially supported by the European Commission under contract ERBFMRX-CT98-0195.

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