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X-ray emission from neutron stars in dark clusters

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Abstract. Two classes of neutron stars may exist in the galactic halo: neutron stars originating in the disk with high velocities and neutron stars originating in globular clusters (via Type II supernovae and/or accretion induced collapse). Moreover, the halo dark matter is likely in the form of dark clusters composed of MACHOs and cold molecular clouds. Here we propose a model in which neutron stars crossing dark clusters in the galactic halo accrete material and emit in the X-ray band. The detection of these X-ray sources whose luminosity can span several orders of magnitude from $\sim 10^{33}$ to $\sim 10^{37}$ erg s^{-1} could be already done by ROSAT.

Key words: dark matter – Galaxy: halo – neutron stars – X-rays: general; stars

1. Introduction

The detection of gravitational microlensing (Paczyński 1986) of stars in the Large Magellanic Cloud (LMC) by the EROS (Aubourg et al. 1993) and the MACHO (Alcock et al. 1993) collaborations shows that MACHOs (Massive Astrophysical Compact Halo Objects) provide a substantial fraction of the dark matter present in the galactic halo (see e.g. De Rújula, Jetzer & Massó 1992). Based on the 6 to 8 microlensing events found so far, the MACHO team (1996) announced that MACHOs contribute a fraction as high as 50% to the halo dark matter.

Quite recently we have proposed a scenario in which the formation of dark clusters composed by MACHOs of mass $\sim 0.1\ M_\odot$ and cold molecular clouds naturally arises in the outer part (beyond $\sim 10-20$ kpc) of the galactic halo (De Paolis et al. 1995a, 1995b, 1996a), while in the inner part of the galaxy stellar globular clusters arise.

Besides dark clusters, the galactic halo could also contain two populations of neutron stars: $\sim 10^9$ neutron stars originating in the disk and ejected in the halo (due to their high kick velocities) and a second population of $\sim 10^6$ neutron stars originating with lower velocities in globular clusters (via Type II supernovae and/or accretion induced collapse of white dwarfs) and also ejected in the halo (due to the low escape velocity from globular clusters). Here we suggest that when these halo neutron stars cross dark clusters passing through molecular clouds, accrete material and emit in the X-ray band.

That old neutron stars can be revealed in the X-ray band due to the accretion of interstellar matter and subsequent X-ray emission has been suggested long ago by Ostriker, Rees & Silk (1970). The problem of the detectability of disk neutron stars has been faced by several authors (Treves & Colpi 1991, Blaes & Madau 1993 and Madau & Blaes 1994) who also recognized that the most favourable sites for the detection of accreting neutron stars are giant molecular clouds in the galactic disk (Colpi, Campana & Treves 1993). However, despite the increasing efforts, only a few X-ray sources have been identified until now as neutron stars accreting the interstellar medium (Walter, Wolk & Neuhäuser 1996).

The existence of a new population of yet unrecognized X-ray sources has been recently suggested by an analysis of very deep ROSAT observations which revealed a considerable excess of faint X-ray sources over that expected by Active Galactic Nuclei (AGN) evolution models (Hasinger et al. 1993). The possibility that this new population of X-ray sources is galactic in origin has been considered by Maoz & Grindlay (1995), which derived the characteristic properties that the unknown population should have to contribute significantly to the diffuse unresolved X-ray background (XRB). The contribution to the XRB of old neutron stars confined in the galactic plane has been also calculated, assuming a given model for this population and taking into account interstellar X-ray absorption (Zane et al. 1995).

ROSAT observations have also revealed a new and distinct class of supersoft X-ray sources with luminosities up to $\sim 10^{38}$ erg s^{-1} (Kahabka, Pietsch & Hasinger 1994). Some of these sources have been optically identified with close binary systems involving mass transfer from a main-sequence star onto a white dwarf burning the accreted matter.

Our main point is that to these populations of X-ray sources can contribute substantially two distinct classes of neutron stars,

Send offprint requests to: G. Ingrosso spherically distributed in the galactic halo and accreting matter from molecular clouds (with mean density between $10^4 - 10^8$ cm^{-3}) inside dark clusters. The first class consists of halo neutron stars (HNS) passing through dark clusters with high (~ 400 km s^{-1}) velocity and producing an X-ray luminosity of $\sim 10^{33}$ erg s^{-1}. The second class consists of neutron stars bound in dark clusters (DCNS) which continuously emit in the X-ray band and that, due to the low (~ 15 km s^{-1}) velocity with respect to the accreting matter, have higher luminosity of $\sim 10^{37}$ erg s^{-1}. We find that HNS may contribute significantly to the diffuse XRB and that some of the supersoft X-ray sources which cannot be identified with any class of known objects can be DCNS.

The presence of accreting neutron stars in the galactic halo could be also tested with observations in the infrared band, because it is well possible that X-rays are (may be in part) absorbed by the surrounding matter and re-emitted in the infrared band. Correlated observations in the radio and X-ray bands could make sure the identification of halo neutron stars still active as pulsars. It goes without saying that the detection of this kind of X-ray halo sources will also provide a further test of the previously proposed model for the galactic dark matter.

In the following Sect. 2 we briefly review our scenario for the dark cluster formation and in Sect. 3 we assess the arguments for the presence of neutron stars in the galactic halo. The expected number of HNS and DCNS and the corresponding X-ray luminosities are discussed in Sect. 4, while the detectability of these sources is faced in Sect. 5. Relevant ROSAT X-ray observations are analyzed in Sect. 6 and, finally, our conclusions are offered in Sect. 7.

2. Dark clusters formation

Our scenario encompasses the one originally proposed by Fall and Rees (1985) for the origin of globular clusters and can be summarized as follows. After its initial collapse, the proto galaxy (PG) is expected to be shock heated to its virial temperature $\sim 10^6$ K. Since overdense regions cool more rapidly than average, proto globular cluster (PGC) clouds form in pressure equilibrium with hot diffuse gas. Below 10^4 K, the main coolants are H_2 molecules and the evolution of the PGC clouds will be different in the inner and outer part of the Galaxy, depending on the decreasing collision rate and ultraviolet (UV) fluxes as the galactocentric distance increases.

In the central region of the Galaxy the presence of an AGN and a first population of massive stars (which act as strong sources of UV radiation that dissociates the H_2 molecules) heavily suppress the cooling and so the PGC clouds remain for a long time at temperature $\sim 10^4$ K. Later on, when the UV flux decreases and after enough H_2 has formed, the cloud temperature suddenly drops and the subsequent evolution leads to the formation of stars and ultimately to globular clusters of mass $\sim 10^6 M_\odot$.

In the outer regions of the halo the UV flux is suppressed (due to the larger galactocentric distance), so that no substantial H_2 depletion actually happens. On top of this, further H_2 is produced via three-body reactions, thus dramatically increasing the cooling efficiency. In such a situation, a subsequent fragmentation of the primordial PGC clouds occurs into smaller clouds that remain optically thin until the minimum value of the Jeans mass $\sim 10^{-2} M_\odot$ is attained, thus leading to the formation of MACHOs clumped into dark clusters. Moreover, since the conversion efficiency of the constituent gas could scarcely have been 100%, in the absence of strong stellar winds the gas remains gravitationally bound in the dark clusters in form of cold molecular clouds. The further possibility that a few percent of the initial gas remains in diffuse form inside dark clusters is not excluded, although its high virial temperature (which would make the gas observable) place stringent limits to its amount.

MACHOs inside dark clusters are detected via gravitational microlensing (possibly as clustered events), while the presence of molecular clouds with expected mass M_m in the range $10^{-3} - 10^{-1}$ $M_\odot$ and radius R_m (from the virial theorem) from 10^{-3} to 10^{-1} pc is difficult to prove due to both their very low temperature - close to that of the Cosmic Background Radiation (CBR) - and low optical depth.

Further details of this scenario can be founded elsewhere (De Paolis et al. 1996a). In particular we also discussed several methods to test the above model and the existence of the halo molecular clouds. Here we remark only that dark clusters can form only at galactocentric distance larger than $R_{min} \sim 10-20$ kpc and that (due to the absence of an "imprinting" mass) we do not expect a characteristic mass for the dark clusters. Indeed, their mass M_{DC} can vary in the range $10^3 - 10^6$ $M_\odot$ and their radius R_{DC} is expected to be between $1 - 10$ pc. Obviously, the above discussion implicitly assumes that the dark clusters have survived until today in the galactic halo. The last issue is surely met if M_{DC} is in the range $3 \times 10^2 - 10^6$ $M_\odot$, as follows from constraints on the evaporation time and close encounters between dark clusters (De Paolis et al. 1996b).

3. Halo neutron stars

Recently it has been reported that radio pulsars are born in the galactic disk with very high velocities (Lyne & Lorimer 1994). If neutron stars have kick velocities of ~ 400 km s^{-1} as implicated by radio pulsar observations (Hartmann et al. 1995), thus most of them have been ejected from the disk and today populates the galactic halo. Assuming a constant supernova rate of $\sim 10^{-2}$ yr^{-1}, one can estimate the presence of $\sim 10^9$ neutron stars in the galactic halo [1]. Some of them, which we named HNS, are crossing today dark clusters accreting matter in molecular clouds and thus emitting in the X-ray band.

Moreover, it is also expected that a second population of neutron stars, born in globular clusters, should exist in the galactic halo. Arguments from both the initial stellar mass function and the observations of a relatively high number of radio pulsars in globular clusters lead to an estimation of $\sim 10^6$ neutron stars born in globular clusters with velocities less than 100 km s^{-1}

[1] This follows from an extrapolation of neutron star birthrate (Narayan & Ostriker 1990) and from the number of supernovae required to account for the heavy-element abundance in the Milky Way (Arnet, Schramm & Truran 1989).

and thus slower then disk pulsars [2]. Since the typical escape velocity of a globular cluster is $\sim$ 30 km s^{-1}, their retention fraction is less then a few percent so that very few neutron stars remain in globular clusters (Drukier 1996). These neutron stars today populate the galactic halo and are expected to be in virial or near virial equilibrium in the galactic gravitational well.

What changes with respect to the neutron stars ejected from the disk is that in the case of neutron stars ejected from globular clusters there is an appreciable chance that some of these objects are captured by the dark clusters (this essentially happens due to the lower relative velocity between dark clusters and neutron stars), making a continuous accretion of the gas in molecular clouds. A neutron star can be captured by a dark cluster only if the relative velocity of these objects is less then the internal dark cluster velocity dispersion ($\sim$ 15 km s^{-1}). Assuming a maxwellian velocity distribution with $\sigma_{DC} \sim 155$ km s^{-1} (corresponding to a flat rotation velocity $\sim$ 220 km s^{-1}), we find that at least a few percent of the neutron stars born in globular clusters are today bound in dark clusters. We refer to this class of $\sim 10^4$ neutron stars as DCNS.

Clearly, we expect very different X-ray features for the two classes of HNS and DCNS as a consequence of both their different velocity with respect to the accreting matter and the time of permanence within dark clusters [3].

4. Collision rate and X-ray flux

Let us now estimate the number of HNS and their consequent X-ray luminosity. We assume a number of $\sim 10^9$ neutron stars spherically distributed in the galaxy (up to the radius $R_h \sim 150$ kpc) and a number of $\sim 10^8\ f\ (10^4 M_\odot/M_{DC})$ dark clusters (assumed for simplicity of the same mass M_{DC}). Here $f \sim 1/2$ is the fraction of dark matter in the form of molecular clouds. According to the standard halo model (see e.g. De Paolis, Ingrosso & Jetzer 1996d), the dark cluster number density is given by

$$n_{DC}(R) = n_{DC}(0) \left(\frac{a^2+R_0^2}{a^2+R^2}\right) \ , \qquad (1)$$

where $n_{DC}(0) \sim 6 \times 10^{-7}\ f\ (10^4 M_\odot/M_{DC})$ pc^{-3} is the local density parameter, $a \sim 5-10$ kpc is the core radius and $R_0 \sim 8.5$ kpc is the local galactocentric distance. In the present case Eq. (1) holds for $R > R_{min}$ which, in our scenario, is the minimum distance at which dark clusters form.

As regard the spatial distribution of the neutron stars, for the sake of simplicity, we assume the same distribution law as for the dark matter in Eq. (1), but with a different core radius b which we take as a free parameter in the range $5-150$ kpc (the latter value giving a near uniform distribution). Correspondingly, the local neutron star number density $n_{NS}(0)$ results in the range $6\times10^{-6}-10^{-7}$ pc^{-3}. Another free parameter of our calculation is the velocity distribution of the neutron stars which we take to be maxwellian with dispersion velocity σ_{NS} in the range $200-600$ km s^{-1}.

The collision rate Γ_{HNS}, i.e. the number of HNS colliding (per second) with dark clusters, is given by

$$\Gamma_{HNS} = n_{DC}(0)\ n_{NS}(0)\ \Sigma\ V_{rel}\ \times$$
$$\int_{R_{min}}^{R_h} \left(\frac{a^2+R_0^2}{a^2+R^2}\right)\left(\frac{b^2+R_0^2}{b^2+R^2}\right)\ 4\pi R^2 dR\ , \qquad (2)$$

where $\Sigma \sim \pi R_{DC}^2$ is the effective cross-section for the collision and V_{rel} the relative velocity between neutron stars and dark clusters. The obtained values of Γ_{HNS} are in the range

$$\Gamma_{HNS} =$$
$$(1-4) f \left(\frac{10^4 M_\odot}{M_{DC}}\right)\left(\frac{R_{DC}}{10\ \mathrm{pc}}\right)^2\left(\frac{V_{rel}}{400\ \mathrm{km\ s^{-1}}}\right) \mathrm{yr}^{-1}, \qquad (3)$$

correspondingly to the extreme cases of $b \sim 150$ kpc and $b \sim 5$ kpc, respectively.

The crossing time of a HNS in a dark cluster is $T_{cross} \sim 3 \times 10^4\ (R_{DC}/10$ pc$)$ (400 km s$^{-1}/V_{rel})$ yr, so that the total number of HNS crossing today dark clusters [4] is $N_{HNS} \equiv \Gamma_{HNS} T_{cross}$. This quantity is found to be independent from V_{rel}, being $N_{HNS} \sim (3-12) \times 10^4\ f\ (10^4 M_\odot/M_{DC})\ (R_{DC}/10$ pc$)^3$.

From Eq. (2) and the definition of N_{HNS}, it is straightforward to obtain the radial dependence of the HNS number density as

$$n_{HNS}(R) = n_{HNS}(0)\ \left(\frac{a^2+R_0^2}{a^2+R^2}\right)\left(\frac{b^2+R_0^2}{b^2+R^2}\right), \qquad (4)$$

where the local number density of HNS is given by $n_{HNS}(0) = n_{DC}(0) n_{NS}(0) \Sigma V_{rel} T_{cross}$ and results to be in the range $(3-140) \times 10^{-10}\ f\ (10^4 M_\odot/M_{DC})\ (R_{DC}/10$ pc$)^3$ pc^{-3} for $b \sim 150$ kpc and $b \sim 5$ kpc, respectively. As one expects, if dark clusters and neutron stars are distributed similarly, crossings happen prevalently in the inner part of the galaxy.

[2] Due to the low metallicity of globular clusters, stars with masses well below $\sim 10\ M_\odot$ (the minimum disk star mass that undergoes supernova explosion) evolve towards supernovae and give neutron stars (Jura 1989). Supernova explosions of less massive stars should be less violent giving neutron stars with lower kick velocities, respect to neutron stars originating in the galactic disk. Another argument leading to the same conclusion comes from the lower expected magnetic field B for these objects. Since in some models the kick velocity of a neutron star is accounted for the asymmetry of B, the lower value of B gives slower neutron stars.

[3] In addition, we should expect a X-ray emission from neutron stars travelling in the galactic halo with a companion star. It is indeed likely that some neutron stars originating in globular clusters retain their companion after the supernova explosion and the ejection in the halo.

[4] Here we suppose that a HNS emits in the X-ray band during the whole crossing time T_{cross}. In fact, taking molecular clouds of mass $M_m \sim 10^{-2} M_\odot$ and radius $R_m \sim 10^{-2}$ pc, we can see that a HNS encounters $\sim$ 50 molecular clouds (along its trajectory inside a dark cluster) and remains inside each molecular cloud for a time $\sim 10^2$ yr.

The instantaneous accretion rate into the surface of a neutron star is described by the Bondi formula (Shapiro & Teukolsky 1983)

$$\dot{M} = 4\pi\lambda \frac{G^2 M_*^2 \ \rho_m}{(a_\infty^2 + V_{rel}^2)^{3/2}} \ , \quad (5)$$

where a_∞ (in the range $0.1 - 10$ km s^{-1}) is the sound velocity in the accreting medium (a molecular cloud at temperature near to that of the CBR), λ is an efficiency constant of order unity, $M_* \sim 1 M_\odot$ is the mass of the neutron star and ρ_m is the accreting matter density. The latter quantity is expected to vary in the range $\sim 10^{-20} - 10^{-16}$ g cm^{-3}, for an internal number density n_m between $10^4 - 10^8$ cm^{-3}. It is also well known that the accreting matter corresponds to the luminosity

$$L_X \equiv \frac{G M_* \dot{M}}{R_*} \quad (6)$$

where $R_* \sim 10$ km is the radius of the neutron star. Therefore, according to ρ_m we have $\dot{M}$ and L_X in the range $6\times 10^{-16} - 6\times 10^{-12}\ M_\odot$ yr^{-1} and $5\times 10^{30} - 5\times 10^{34}$ erg s^{-1}, respectively.

The luminosity L_X in Eq. (6) strongly depends on the value of V_{rel} which enters with the inverse cube power. Thus, for the same values of the density ρ_m, slower neutron stars have higher X-ray luminosities. In the framework of our scenario, we expect in particular that for the DCNS V_{rel} is of the order of the velocity dispersion (~ 15 km s^{-1}) inside dark clusters. Therefore, DCNS continuously accrete and emit X-rays with a luminosity $L_X \sim 10^{37}\ (n_m/10^6$ cm$^{-3})$ erg s^{-1} .

The effective temperature T_X of the emitting region on the surface of the neutron star can be estimated (assuming a black body emission) by using the relation $L_X = \sigma A T_X^4$, where A is the area of the emitting region (Shapiro & Teukolsky 1983). In the case of magnetized neutron stars, the incoming material is channeled to the poles along the magnetic lines and $A \sim \pi R_*^3/r_A$, where $r_A \sim (B^4 G M_* R_*^{10}/2L_X^2)^{1/7}$ is the Alfvén radius. Therefore, the effective temperature of the emitting region can be expressed in the form

$$T_X \sim 5\times 10^6 \left(\frac{L_X}{10^{33}\ \mathrm{erg\ s^{-1}}}\right)^{5/7} \left(\frac{B}{10^9\ \mathrm{gauss}}\right)^{4/7} \mathrm{K}, \quad (7)$$

which implies substantial emission in the X-ray band, for a large range of values of L_X and B.

5. The observability of accreting neutron stars in dark clusters

How many HNS and DCNS should be present per square degree in the halo at large galactic latitude? In the case of the HNS, by using the value $N_{HNS} \sim (3-12)\times 10^4\ f$, this number is in the range $0.4 - 1.5$ objects per square degree (depending on the assumed neutron star core radius), if we take $f \sim 1/2$. In the case of the DCNS, their total number is $\sim 10^4$ independently from the dark cluster parameters, so that we expect ~ 0.3 DCNS per square degree.

However, the gas constituting molecular clouds diminishes (due to X-ray absorption) the number of accreting neutron stars that can be seen by a satellite. In particular, the expected number of HNS and DCNS in the field of view of a X-ray satellite has to be computed considering only those sources whose unabsorbed flux in the instrumental energy interval is above the sensitivity limit. The ROSAT satellite operating in the energy range $0.1 - 2.4$ keV is by far the more sensitive X-ray detector, having a sensitivity at the threshold of $\sim 10^{-16}$ erg cm^{-2} s^{-1}. For comparison, the energy flux on the Earth of an unabsorbed X-ray source at a distance D is $\Phi_X \sim 10^{-14}\ (L_X/10^{33}$ erg s^{-1})(25 kpc$/D)^2$ erg cm^{-2} s^{-1}, showing that absorption is a crucial effect for discussing the detectability of HNS.

The absorption cross section in the ROSAT energy band for incoming X-rays on gas with interstellar composition can be parameterized in terms of the energy E (expressed in keV) as $\sigma_X(E) \sim 2.6\times 10^{-22} E^{-8/3}$ cm^{-2} (Morrison & McCammon 1983) [5]. The corresponding values of $\sigma_X(E)$ result to be in the range $10^{-19} - 10^{-23}$ cm^{-2}, implying that gas column densities of $\sim 10^{22}$ cm^{-2} could be sufficient to obscure the emitted X-rays. This column density, for a single molecular cloud with $n_m \sim 10^6$ cm^{-3} corresponds to a distance of the order of R_m and this makes more likely the observation of neutron stars located only in the outer layer of dark clusters.

Actually, the previous values for σ_X have to be considered as upper limits, since we expect that molecular clouds have a lower metallicity (up to $\sim 10^{-4}$ with respect to the solar one, see De Paolis et al. 1996b). Indeed, for a low metallicity gas $\sigma_X(E)$ decreases significantly (see Fig. 1 in Morrison & McCammon 1983). This has a substantial effect in the energy range 1 keV $< E <$ 2.4 keV but already at $E \sim 0.5$ keV the effect of assuming a low metallicity gas reduces the absorption cross section of a factor ~ 5.

It is also known that UV and X-ray emission from a neutron star accreting in a molecular cloud ionize the ambient gas producing a HII region of dimension up to $10^{-2} - 10^{-1}$ pc (Kallman & McCray 1982) for a X-ray luminosity $L_X \sim 10^{37}$ erg s^{-1}. This is relevant for DCNS, while in the case of HNS which have lower luminosity and move with high velocity through the accreting matter, a cometary structure of HII gas is instead produced with transverse dimension $10^{-4} - 10^{-3}$ pc. Since ionization of hydrogen and helium reduces significantly the X-ray absorption (ionization of metals is not influent), the formation of these HII regions should help the visibility of accreting neutron stars.

Therefore, effects of low metallicity, ambient ionization as well as consideration of geometrical filling factor for molecular clouds in dark clusters should make observable DCNS in any position inside dark clusters. On the contrary, HNS should be detectable (at least in the mid $0.5 - 0.9$ keV and high $0.9 - 2.0$ keV ROSAT bands) only if located in an external layer with

[5] The functional dependence on energy of $\sigma_X(E)$ implies, due to the more efficient absorption at low energy, a hardening of the observed X-ray spectra.

thickness of a few pc. This reduces roughly to one half the number of observable HNS so that we expect $\sim 0.2-0.8$ objects per square degree in the ROSAT field of view.

Actually, the dark cluster parameters are largely unknown and the expected number of HNS could substantially change if we take different values for the mass and radius. Moreover, as we have seen, X-ray absorption (besides molecular cloud parameters) also depends on the typical expected X-ray spectrum which, in turn, for low luminosity objects shows an overall hardening with respect to the blackbody at the neutron star temperature in addition to a significant excess over the Wien tail (see Zampieri et al. 1995). In conclusion, to perform a more quantitative determination of the expected number of HNS in the ROSAT field of view one needs to select values for a number of parameters which at the moment are largely unknown.

So far we discussed the possibility to detect HNS as isolated objects. However, it is also possible that unabsorbed X-rays from (unresolved) HNS contribute to the diffuse XRB. Parameterizing a generic point in the halo by coordinates (r, θ, ϕ) and taking the Earth as the origin, the expected X-ray flux per unit solid angle is given by

$$\Phi_X(\theta,\phi) = \epsilon \int_{r_{min}}^{r_{max}} n_{HNS}(r)\ \frac{L_X}{4\pi r^2}\ r^2 dr\ , \qquad (8)$$

where the HNS number density $n_{HNS}(r)$ is given by Eq. (4) with $R = (r^2 + R_0^2 - 2rR_0 \cos\theta\cos\phi)^{1/2}$ and the factor ϵ has been introduced to account for the X-rays absorption by the halo gas in the dark clusters. The best chance to detect X-rays in question (avoiding absorption from interstellar gas) is provided by observations at high galactic latitude, and so we take $\theta = 90^0$ in Eq. (8). Therefore, if we assume $f \sim 1/2$ and $\epsilon \sim 1/2$, we get $\Phi_X(90^0) \sim 1.9\times 10^{-15} - 2.9\times 10^{-14}$ erg cm^{-2} s^{-1} deg^{-2} in the case b = 150 kpc and b = 5 kpc, respectively. This flux, for the effective temperature values given by Eq. (7), prevalently falls within the ROSAT energy band.

As a final point we note that if absorption is relevant, reprocessing of X-rays into infrared (due to vibrational-rotational transition of H_2) should give rise to an infrared luminosity $L_{IR} \sim 10^{-3}\ L_X$ (Lepp & MacCray 1983). Also radio observations of free-free continuum and recombination line emission in the HII regions around accreting neutron stars could also be observed together with X-rays.

6. Relevant X-ray observations

It is well possible that the ROSAT satellite could have already detected neutron stars accreting in dark clusters. Here we mention some observations relevant for our scenario.

The longest pointed observations with the ROSAT PSPC in the direction of the Lockmann Hole (with the lowest neutral hydrogen column density) revealed the presence of 413 resolved sources per square degree at the faintest flux level (Hasinger et al. 1993). These sources constitute a statistically complete sample in the hard band with fluxes between $S = 2.6\times10^{-15}$ and 4.8×10^{-13} erg cm^{-2} s^{-1} and a maximum of objects at $\sim 10^{-14}$ erg cm^{-2} s^{-1}. The $LogN - LogS$ diagram clearly indicates a factor 1.6 more sources than predicted by standard models for AGN X-ray luminosity function. As suggest by Hasinger et al., one way to remedy this discrepancy might be to adopt different parameters or more complicated evolutionary models for AGN. Another possible explanation would be the existence of a new population of faint sources (with a rather steep $LogN - LogS$ function) which cannot be identified with any class of known objects (as stars, BL Lac objects, clusters of galaxies and normal galaxies). Such a population could be practically absent at fluxes greater than a few 10^{-14} erg s^{-1} cm^{-2} but could contribute with $\sim$ 120 sources per square degree at the faint flux level. Therefore, since we estimated that less than $\sim$ 1 HNS per square degree should be observable, our proposed X-ray emitting HNS can contribute only up to $\sim 1\%$ to this class of unknown objects.

Hasinger et al. (1993) also found that about 60% of the XRB is resolved to discrete sources with flux (averaged over the directions to 27 fields at high galactic latitude $|b| \geq 30^0$) that amounts to 3.6×10^{-13} erg cm^{-2} s^{-1} deg^{-2} in the $0.5-2$ KeV band. The total XRB intensity (averaged over the analyzed fields) is 6×10^{-13} erg cm^{-2} s^{-1} deg^{-2}. As we have seen at the end of the previous section, the unabsorbed X-ray flux at high galactic latitude [6] from (unresolved) HNS is estimated to be in the range $\sim 1.9\times10^{-15} - 2.9\times10^{-14}$ erg cm^{-2} s^{-1} deg^{-2}, depending on the core radius b of the neutron star distribution in the galactic halo (the lower value is for b = 150 kpc, the higher one for b = 5 kpc). This implies that the contribution of the HNS emission to the XRB excess (with respect to the discrete sources) can be in the range $\sim 0.8\% - 10\%$ so that, at least in the the case of HNS distributed as the dark matter, their contribution to the XRB excess can be significant.

Recently, Maoz & Grindlay (1995) showed that a new galactic population of faint ($L_X \sim 10^{30} - 10^{31}$ erg s^{-1}) X-ray sources with scale height of a few kpc can explain the XRB excess as well as the $\sim$ 120 sources per square degree required by the Hasinger et al. analysis. However, these authors have ruled out the possibility that accreting neutron stars could be the new population on the basis of the very soft spectrum (outside the ROSAT energy range) expected for low luminosity objects. This possibility has been reconsidered by Zane et al. (1995) which noted that the emission from magnetized neutron stars is harder than that expected from a black body at the neutron star effective temperature, since the accretion is channeled into polar caps so diminishing the emitting area. These authors have also calculated the actual emerging flux from low luminosity objects (by using the method in Zampieri et al. 1995) showing that up to $\sim 12\% - 25\%$ of the unresolved soft excess at high galactic latitude in the XRB can be explained in terms of neutron stars (in the galactic disk) accreting interstellar matter. In analogy, we note that X-rays emitted from HNS of luminosity $\sim 10^{33}$ erg s^{-1} and magnetic field $\sim 10^9$ gauss should emit - due to Eq. (7) - X-rays with mean energy of $\sim$ 0.2 keV, which is within the ROSAT energy band.

[6] A similar result is obtained by averaging the flux calculated by Eq. (8) over the directions considered by Hasinger et al. (1993).

ROSAT observations during the All-Sky Survey and deep pointing, have also revealed a new and distinct class of supersoft X-ray sources with luminosities from a few times 10^{37} erg s^{-1} up to $\sim 10^{38}$ erg s^{-1} (Kahabka, Pietsch & Hasinger 1994). These are among the softest X-ray sources characterized by a black body spectrum with a temperature roughly a few times 10 eV and with most of the X-ray emission below 0.5 keV. While five sources have been detected towards both the LMC and the SMC and 16 have been discovered in M 31, only very few have been found in the Galaxy (Greiner 1996a).

Supersoft X-ray sources are a collection of different type of objects (single non interacting white dwarfs, central stars of planetary nebulae, PG 1159 stars, symbiotic variables, magnetic cataclysmic variables, active galactic nuclei) which, generally, are recognized after follow-up optical observations.

Some of the sources in the Magellanic Clouds have been optically identified with close binary systems involving mass transfer from a main-sequence star onto a white dwarf burning the accreted matter (van den Heuvel et al. 1992). ROSAT observations established these supersoft X-ray sources as a distinct class which is named SSS (see Greiner 1996a). As far as M 31 is concerned, the supersoft X-ray sources location distribution suggests that they belong to a disk population, while their identification with any known class of objects is under discussion (Greiner, Supper & Magnier 1996).

Another possible class of supersoft X-ray sources are old isolated neutron stars shrouded by super-Eddington accretion rates which emit a soft spectrum due to the presence around them of extended Compton scattering clouds (Greiner, Hasinger & Kahabka 1991; Kylafis & Xilouris 1993). Two sources located in the galactic disk have been proposed to be such neutron stars and one of these (RX J1856.5-3754) is a bright source also seen by ROSAT (Walter, Wolk & Neuhäuser 1996).

Remarkably enough, in our scenario DCNS have the same X-ray luminosity of the supersoft X-ray sources and, if located in the inner regions of dark clusters (with density in excess with respect to the assumed value of $\sim 10^6$ cm^{-3}), they could make a super-Eddington accretion and have Compton scattering clouds. Accordingly, DCNS could emit a spectrum softer than that predicted by Eq. (7) for high luminosity objects. A second reason for a softer spectrum is that DCNS (being born in globular clusters) are expected to have lower magnetic fields with respect to neutron stars ejected from the galactic disk (see discussion in footnote 2). Therefore, it appears natural to suggest that some of the unidentified supersoft X-ray sources can be DCNS, for which we estimated an occurrence of ~ 0.3 sources per square degree.

Very recently a systematic search for supersoft X-ray sources has been undertaken using the ROSAT All-Sky Survey data, with emphasis on the galactic population (Greiner 1996b). The selection criterion based on the hardness ratio led to 143 sources which, after optical identification with any known class of objects, came up to 12 unidentified objects. It is well possible that some of these objects are DCNS (also visible in the optical band due to the presence of a thick atmosphere extending up to large distance around the neutron star). However, it is also possible that the conservative approach adopted to select supersoft X-ray sources (for instance, in the Greiner 1996b search only 7 out of the more than 30 known supersoft X-ray sources are members of the sample) could have made DCNS undetected until now. It is without saying that our proposed identification of DCNS with a distinct class of supersoft X-ray sources is well possible, but in any case more detailed observations are needed.

Finally we mention the detection by ROSAT of shadows in the 1/4 keV X-ray background toward high-latitude interstellar clouds in Draco (Burrows & Mendenhall 1991, Snowden et al. 1991). Data show that about half of the emission originate beyond the clouds. More recent observations show that other halo spots may exist in a region of almost 300 deg^2 in Ursa Major (Snowden et al. 1994) and in a region of angular size of 25×25 deg^2 in Eridanus (Snowden et al. 1995). These observations are interpreted as a first direct evidence for the presence of a million-degree galactic halo gas. The derived total X-ray luminosity of this diffuse gas (which can only accounts for less than a few percent of the galactic dark matter) is $\sim 10^{39}$ erg s^{-1}, in agreement with the X-ray observations for other spirals (Fabbiano 1989). It is straightforwards to say that in our scenario a population of unresolved HNS and DCNS could significantly contribute to this diffuse X-ray emission.

7. Conclusions

In this paper we have shown that two different populations of halo neutron stars, accreting matter from molecular clouds present in the dark clusters (which compose the galactic dark matter) can be revealed in the X-ray band. The X-ray luminosity of the halo neutron stars (HNS) crossing dark clusters should be $\sim 10^{33}$ erg s^{-1}, while that of the neutron stars bound in dark clusters (DCNS) is expected to be about 10^{37} erg s^{-1}. We estimate the presence of ~ 1 object per square degree for each population of neutron stars. HNS may contribute substantially to the unresolved soft excess observed at high latitude in the XRB, while DCNS can be tentatively identified with some of the supersoft X-ray sources for which the identification with any known class of objects is missing. A correlation with the emission in other wavelengths (infrared and radio) due to absorption from the surrounding medium and/or pulsar activity can be expected in some cases.

As a final point we note that the detection of these X-ray halo sources can provide an independent test on the presence of baryonic dark clusters in the galactic halo. Moreover, we would like to mention that neutron stars in the galactic halo can be directely detected by microlensing experiments (Mollerach & Roulet 1996) and altough their expected optical depth is $\sim 10^{-2}$ respect to the MACHOs optical depth, it is likely that experiments planned for the near future will detect these objects.

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