Population synthesis as a probe of neutron star thermal evolution

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Abstract. The study of thermal emission from isolated, cooling neutron stars plays a key role in probing the physical conditions of both the star crust and the core. The comparison of theoretical models for the star thermal evolution with the surface temperature derived from X-ray observations of sources of different age is one of the main tools to investigate the properties of the interior and constrain the equation of state. Here we propose to use population synthesis studies as an independent approach to test the physics governing the star cooling. Theoretical Log N-vs-Log S distributions depend on the assumed neutron star thermal evolution. We have computed distributions for several different cooling scenarios and found that comparison with the observed Log N-Log S of isolated neutron stars is effective in discriminating among cooling models. Among the eleven cooling models considered in this paper, all of which may reproduce the observed temperature vs. age diagram, only at most three can explain the Log N-Log S distribution of close-by cooling neutron stars. The Log N-Log S test, being a “global” one and despite some limitations, appears indeed capable of complementing the standard temperature vs. age test used up to now.

Key words. stars: evolution — stars: neutron — X-rays: stars

1. Introduction

The determination of the equation of state (EOS) at or above nuclear densities is a long sought goal in high energy astrophysics. In this respect direct observations of neutron stars (NSs) may provide invaluable insight into several key issues of fundamental physics, like quantum chromodynamics/electrodynamics, superfluidity and superconductivity, that could not be otherwise tested under laboratory conditions. An ideal way to place tight constraints on the EOS is the simultaneous mass and radius measurement of NSs (see e.g. Lattimer & Prakash 2001). Precise mass determinations have been obtained for NSs in binaries, especially in radio pulsar systems (e.g. Thorsett & Chakrabarty 1999). Simultaneous mass and radius measurements are presently available for a few X-ray binaries, although masses derived from gravitational redshift of spectral lines are still uncertain in many cases (e.g. Cottam et al. 2002). Mass estimates can be obtained also from quasi-periodic oscillation measurements (Bulik et al. 2000), but results based on this, as well as other approaches, are still quite model dependent. The study of glitches observed in radio pulsars, and recently in anomalous X-ray pulsars (AXPs) as well (e.g. Horvaths 2004, Dall’Osso et al. 2003), promise further insight into the understanding of the internal structure of NSs, as well as future observations of neutrino and gravitational wave emission from neutron star sources.

For the time being, however, X-ray observations of NSs are, and will still be for some time, central for our understanding of the star interior. Isolated neutron stars that emit at X-ray energies as they cool are particularly promising in this respect. Their thermal radiation directly comes from the star surface, carrying information on the physical conditions of the emitting matter, in particular on the star surface temperature. Thermal X-ray emission has been detected from about 20 isolated NSs so far, including normal radio pulsars, central compact objects in supernova remnants (CCOs in SNRs), radioquiet NSs, AXPs and soft $\gamma$-repeaters (see e.g. Pavlov & Zavlin 2002, Kaspi et al. 2003, Haberl 2004 for reviews).

Significant progress in the understanding of NS thermal evolution has been made in recent years and cooling curves have been computed by several groups...
The paper is organized as follows. In section 2 we discuss the advantages and limitations of the two methods in extracting information from observational data. Section 3 presents our population synthesis model in more detail, especially concerning the choice of the set of cooling curves which will be used in our calculation. We present our results and discuss them in section 4. Section 5 contains our conclusions.

2. The two tests

In this section we briefly discuss and compare the capabilities of the conventional T-t test and of the Log N-Log S test we propose here. Our main conclusion is that the two approaches should be used together as their advantages and disadvantages are mostly complementary to each other especially in the case of available samples of observed objects.

2.1. The T-t test

The T-t test is the most appropriate one to compare results of thermal evolution calculations with observations. An important advantage of this test is that there are no additional theoretical uncertainties except those connected with the cooling model: theoretical cooling curves do not depend on unknown (or poorly known) astrophysical parameters but only on the input physics of the star interior (for a discussion of cooling processes and references to earlier papers, see e.g. Yakovlev et al. 1999 and Blaschke et al. 2004). Still, there are some well known drawbacks to this method.

For sources associated with radiopulsars or CCOs, the star age is usually estimated from the spindown age $P/\dot{P}$, or inferred from the age of the supernova remnant. To which extent these determinations are indeed representative of the neutron star age is still uncertain. The situation is even worse for ROSAT isolated neutron stars which are not associated with a SNR and are with no exception radio-silent. Current age estimates for the two brightest objects in this class (RX J1856.5-3754 and RX J0720.4-3125), based on dynamical considerations, should be regarded only as guesses.

The T-t test is not very sensitive to objects with ages $\lesssim 10^5$ yrs. There are two reasons for this. First, there are only a few sources older than this value to which the test can be applied. Then, cooling curves sharply drop at the photon cooling stage. Shifts between different cooling curves are comparable with data error bars. So, it is difficult to discriminate between models that differ mainly in this respect.

Cooling calculations provide the star temperature at the core-crust boundary and the actual surface temperature is then obtained applying a bridging formula (e.g. Tsuruta 1979; Yakovlev et al. 2004). Detailed modeling of heat transport in the highly magnetized envelope indicates that the temperature surface may be influenced by several effects, among which the magnetic field distribution inside the star is very important (Geppert et al. 2004). The temperature is derived from a spectral fit to the data and, as such, depends on the assumed emission model for the surface. Different models (blackbody, H/heavy elements at-
perature estimates are available\(^1\). Clearly these sources are not representative of any real population of NSs.

2.2. The Log N-Log S test

The Log N-Log S distribution is a widely used tool in many branches of astronomy. For isolated NSs such an approach has been already used by Neuhauser & Trümper (1999) and Popov et al. (2000) to probe the origin of isolated NSs in the solar proximity. The main conclusion of these investigations is that the observed Log N-Log S cannot be easily explained assuming that the local population of NSs originated only in the Galactic disc. As shown in Paper I and II, accounting for massive progenitors in the Gould Belt reconciles theoretical predictions with the data.

One immediate advantage of the Log N-Log S test is that, at variance with the T-t test, no degree of arbitrariness is introduced when observational data are analyzed: both the fluxes and (of course) the number of sources are well measured. In addition, this approach is a “global” one. In our scenario it would not be possible to explain some particular sources by invoking slight changes in the cooling physics. Once the parameters of the model other than those related to the cooling process are fixed (see section 3), a particular cooling curve either fits the population as a whole or not. Furthermore, the Log N-Log S sample is a uniform one, i.e. objects are flux (and probably volume) limited, and no strong selection criteria are introduced.

For the Log N-Log S test the only necessary observational piece of information is the ROSAT count rate. The method can be applied to objects with unknown ages. This makes it possible to include, for example, all the ROSAT X-ray dim NSs, and 3EG J1835+5918 (the Geminga twin) in the testing sample. The Log N-Log S test is mostly sensitive to NSs older than \(\sim 10^5\) yrs. Older sources dominate in number, and in the solar proximity there are about a dozen of them in comparison to very few with \(t \lesssim 10^5\) years.\(^2\)

Nevertheless there are significant limitations too. One source of uncertainty is our incomplete knowledge of some important ingredients of the population synthesis model. These are discussed in more detail in the next section and concern the spatial distribution of the NS progenitors, the NS mass and velocity spectrum, and their emission properties. However, all these issues, to some extent, can be addressed by considering different cases believed to cover the entire range of acceptable scenarios. In addition, there could be unknown correlations among some of the quantities we use to parametrize our model, so that they should not be treated as independent ones. Examples of such possible correlations are those between the star kick and the internal structure (because of quark deconfinement, see Bombaci & Popov 2004), and between the star mass and the magnetic field (because of fallback, see Popov et al. 2002, Heger et al. 2005). A more severe problem arises in connection with the low statistics of the sample, since there are only about 20 thermally emitting NSs known to date. This implies that the bright end of the Log N-Log S relation comprises very few objects so that it is difficult to account for statistical fluctuations. We do not know much either about the properties of very faint sources, i.e. the dim end of the Log N-Log S distribution.

3. The population synthesis model

The main physical ingredients that enter our population synthesis model are:

- the initial NS spatial distribution;
- the kick velocity distribution;
- the NS mass spectrum;
- the cooling curves;
- the surface emission;
- the interstellar absorption.

The calculation of the NS spatial evolution as they move in the Galactic gravitational potential follows that presented in Papers I and II. The same treatment of the interstellar absorption is retained and the kick distribution is that proposed by Arzoumanian et al. (2002). We do not account for atmospheric reprocessing of thermal radiation, and assume that the emitted spectrum is a pure blackbody. Although this is clearly an oversimplification, it is a reasonable starting assumption and will serve for our, mainly illustrative, purposes. A more detailed description of surface emission may be easily accommodated in our model later on. For the time being, we perform our calculations for nine different sets of cooling curves among those discussed in Blaschke et al. (2004), hereafter BGV, to which we refer for all details. This issue, together with the initial spatial distribution of NSs and their mass spectrum, is further discussed below.

3.1. The initial NS spatial distribution

Following the results of previous investigations (paper I), we take as an established fact that the population of nearby NSs is genetically related to the Gould Belt. The contribution of the Belt has dominated the production of compact remnants in the solar proximity over the past \(\sim 30\) Myrs (see Poppe 1997 for a detailed description of the Belt structure). About two thirds of massive stars in the \(\sim 600\) pc around the Sun belong to the Belt.
3.2. The NS mass spectrum

Since cooling curves are strongly dependent on the star mass, the mass spectrum is one of the most important ingredients and, unfortunately, one of the lesser known. We cannot rely on the mass measurements in binary radio pulsars (e.g. Thorsett & Chakrabarty 1999) because they refer to a “twice selected” population (i.e. selection effects due to evolution in a binary can be important together with possible conditions necessary for radio pulsar formation). Probably not all NSs go through the active radio pulsar stage (e.g. Gotthelf & Vasisht 2000), and the properties of NSs in binaries may be different to those of isolated objects (e.g. Podsiadlowski et al. 2003). Note that the local NS mass spectrum can be different to the global NS mass spectrum in the Galaxy. Even stronger deviations can be expected between the mass spectra of local NSs and of those sources usually used for the T-t plot.

As the population of NSs in ∼ 1 kpc around the Sun may be slightly different from the average galactic population, we estimated the mass spectrum for these objects directly (see Paper II for more details). The basic idea is to use HIPPARCOS data on massive stars around the Sun in conjunction with the calculations by Woosley et al. (2002). Knowing the mass distribution of progenitors through their spectral classes, we use a fit to a plot from Woosley et al. (2002) in order to obtain the NS mass from the mass of the progenitor.

We use eight mass bins centered at $M/M_\odot = 1.1, 1.25, 1.32, 1.4, 1.48, 1.6, 1.7, 1.76$. The adopted mass spectrum is shown in Fig. 1. The lower limit for the NS mass is still an open question. Timmes et al. (1996) suggested that there are no NSs with $M \lesssim 1.27M_\odot$, although their conclusion is not definite (see also Woosley et al. 2002) for this reason we decide to use also a truncated mass spectrum, in which the first bin is suppressed and all objects originally contained there are added to the second one. Each bin corresponds to one of the calculated cooling curves. According to the mass spectrum, each curve has a statistical weight of 31%, 25.75%, 11%, 28.125%, 8.75%, 1.125%, 0.75%, and 0.625%. For the truncated one the weights of the first two bins are replaced by 0.0 and 57.5% respectively. We note that sampling also relatively low masses is important since low-mass NSs seem to be required to interpret data on the T-t plot (BGV).

3.3. Cooling curves

In their recent paper Blaschke et al. (2004) presented sixteen sets of cooling curves. Each set contains models for several values of the star mass while different sets refer to different assumptions on heat transport in the crust and on the physical processes in the NS interior. Five of these models are unable to reproduce the observed temperature-age plot and will not be considered further. From the remaining eleven sets, all of which give results not in contradiction with observations (see, however, the discussion in sec. 4), we select nine representative models for our population synthesis calculations (models I - IX in Table 1). We add two models (X and XI) from the recent analysis in G05, which correspond to models III and VII, respectively, when calculated with different crustal properties. All of them have superfluid nuclear matter and medium modifications of the neutrino processes. They differ in the assumptions about the superfluid gaps, the presence/absence of a pion condensate and the properties of the neutron star crust. The latter governs the relationship between the temperature of outermost core layer ($T_{in}$) to that of the star surface ($T_s$). The main characteristics of the selected models are summarized in Table 1. All of the eleven models satisfy the temperature - age test according to BGV, whereas only six of them fulfill the additional brightness constraint introduced in G05. The last column anticipates the results discussed in the following section and shows if the model complies with the Log N-Log S test.

4. Results and discussion

In each run we calculate 5000 individual tracks for the spatial evolution of a single star with a time step of $10^4$ yrs.
Fig. 2. Model I. Left: cooling curves for (from top to bottom) 1.1, 1.25, 1.32, 1.4, 1.48, 1.6, 1.7, 1.76 M⊙. Right: the corresponding Log N-Log S distribution for R_{belt} = 300 pc and non-truncated mass spectrum (full line) and 500 pc and truncated mass spectrum (dotted line). See text for details.

Fig. 3. Same as in Fig. 2 for Model III. The dashed line refers to a calculation in which the full (non-truncated) mass spectrum was used and R_{belt} was assumed to be 500 pc. Model X should produce nearly the same Log N-Log S distribution as it differs only in the type of the crust.

Each track is applied to all eight (or seven for the truncated spectrum) masses, and the thermal evolution is followed by the corresponding cooling curve. Results are then collected according to the statistical weight of each mass bin.

Results are summarized in Table 1 and Figs. 2-7 which refer to a selected sub-sample of the cooling curve sets listed in that Table. In the left panels of Figs. 2-7, the corresponding cooling curves for the various masses are shown. Results are plotted for ages > 10^4 yrs and temperatures above 10^5 K. The right panels illustrate the Log N-Log S distributions computed for the same sets of cooling curves. All models have been calculated using both the full mass spectrum and the truncated one, although results for the latter are not shown in all cases (see the following discussion). Two values of the outer radius of the Gould Belt have been used to test the dependence of our calculation on the assumed geometry, R_{belt} = 300 pc and 500 pc.
Fig. 4. Same as in Fig. 3 for Model VI. Model IV gives quite similar results since the change of the crust model from C to E does not affect the log N - log S distribution.

Fig. 5. Same as in Fig. 4 for Model VII. Model XI should produce nearly the same Log N-Log S distribution as it differs only in the type of the crust.

Theoretical distributions are superimposed on the observed Log N-Log S for isolated NSs. The data points are derived from the sample of thirteen sources listed in Paper I. Error bars correspond to Poisson statistics and are plotted to illustrate the statistical significance of the points. We note, however, that there can be more unidentified sources, especially at fluxes below 0.1 cts s$^{-1}$ (see Rutledge et al. 2003 for a recent discussion). In this respect, the fact that the two points at the lowest fluxes lie below the general trend of the observed Log N-Log S is not surprising. In addition, the observational upper limit derived by Rutledge et al. (2003) on the number of fainter sources is also shown (marked as BSC in the figures). Bounds on the total number of sources with flux $>0.2$ cts s$^{-1}$ have been also presented by Schwone et al. (1999), on the basis of the ROSAT Bright Sources Catalogue (BSC).

The comparison of the predicted and observed Log N-Log S distributions in Figs. 4 and 5 indicates that at most three cooling models (model I and possibly models VIII and IX) are in agreement with the data. All the others substantially overpredict the observed number of sources.
at all fluxes, even though they comply with the T-t test. This latter statement deserves further comment. BGV did not reject models II–VII on the basis of the fact that the cooling curves cover, for the assumed mass range, the entire region in the T-t plane where the observed sources lie. This approach is sound, and it represents the only possible option to discriminate among different cooling scenarios at the zero level, i.e. without introducing additional information. Clearly, if some assumptions on the NS mass distribution are made, the T-t test can be used to exclude some further models. If the same mass distribution discussed in Sec. 3.2 is applied to BGV sets of cooling curves, one is immediately led to discard models II–V and VII because they predict quite high temperatures for low mass NSs ($M \lesssim 1.3M_\odot$) which, according to our mass spectrum, are very abundant. Although such hot objects would be detectable even to large distances they are not actually observed (this issue is further discussed in G05, see also below). However, care must be taken in using such an argument. Our mass spectrum is meant to be representative of the local population of isolated NSs, and its application to the very biased and limited sample of objects which can be placed on the T-t plots is uncertain. Nevertheless, one can reverse the argument by saying that the two tests, when provided with the same amount of information, yield results that are broadly consistent, as they should. Still,
we note that a strict interpretation of the Log N–Log S test results in the exclusion of two further models (VI and VIII) and that even in the most optimistic case model VI is rejected.

The Log N-Log S test is not equally sensitive to changes in the three main groups of parameters in Table I (presence or absence of the pion condensate, gaps, and type of the crust). Mostly the test reacts to changes in the gap parameters. Conversely, changes in the type of the crust are not very important as here we consider a sample of relatively old NSs (nevertheless uniform samples of younger NSs can also be studied). Variations in the crust properties are discussed in detail in G05, where the brightness constraint was introduced. G05 shows that models II–V and VII can be ruled out when the absence of very bright young NSs is considered as a constraint. The fact that the Log N-Log S test leads to the same conclusion is however a completely independent result, since objects from different age ranges are used in the two approaches.

As mentioned earlier, the Log N-Log S test applied to close-by NSs is not sensitive to changes in the crustal properties. This implies that if a cooling model with a given crust is rejected then its variants with other types of crust (at least from the set considered here) can be ruled out, too. For example, additional models X and XI (see Table I) do not satisfy the test because their twins (models III and VII, respectively) do not (see Figs. 3 and 4). In G05 it has been shown that it is possible to fulfill the BC by changing the crust. For example, model III with crust E can fit the data. However, on the basis of the Log N-Log S test this model is ruled out. This is because the latter test mainly “feels” the changes in gaps. And if they are “wrong” then changes in the crust properties are of no avail.

Jumping to the conclusion that the present analysis can provide direct information on the physical state of star interior would be premature. Our adopted scenario contains a number of uncertainties, as discussed in sections 2 and 4. Nevertheless, we believe that the case presented here convincingly shows that by combining theoretical cooling curves with populations synthesis calculations one has the potential to discriminate between competing cooling scenarios. The main outcome of this investigation is not that models I, and possibly VIII and IX, fit the data while others do not. This may be the result of our starting assumptions. What matters is the fact that, within the same set of assumptions, different cooling models produce different results when compared with observations.

Current limitations of this approach are due to our present incomplete knowledge of some key issues, chiefly the NS mass spectrum, their surface emission properties and initial spatial distribution. We attempted to account for some of these uncertainties in our model by considering different configurations which should bracket the true behavior. We note that in all the six cases for which no agreement has been found between theoretical and observed distributions, this is largely independent of the assumptions we introduced. Using different values of \( R_{\text{belt}} \) or taking variants of the mass spectrum does not help in reconciling predictions with the data. However, we caution that other effects, like those introduced by the proper inclusion of an atmospheric model, may be important. This, and other issues, will be the subject of future work.

In all the cases we examined (see again Figs. 2-7), with the possible exception of model VIII, the capability of our test to discriminate between different cooling scenarios seems to be quite robust. The three models (I, VIII and IX) which can reproduce the observed Log N-Log S for our choice of parameters have also been considered by BGV as the most realistic ones. Among models I–IX which according to BGV are not in contradiction with the Temperature–age test, the three mentioned above are the theoretically most appealing ones since either the super-fluid gaps were calculated with the same nucleon-nucleon interaction that formed the basis for the equation of state and thus the structure of the neutron star configurations (models I and IX) or the gaps were modelled such as to mimic these results (model VIII).

### 5. Conclusions

In this paper we suggest adopting the Log N-Log S test as an useful addition to the standard T-t test in probing neutron star cooling models. To illustrate the capabilities of the proposed approach, we applied it to nine sets of cooling curves from [Blaschke et al. (2004)] Out of sixteen sets described in that paper and two additional ones taken from [Grigorian (2005)], these eleven produce results that are not in immediate contradiction with the T-t test. The application of the Log N-Log S test rules out at least eight out of eleven investigated cooling models, resulting in just three models able to pass both tests. Requiring that the tested cooling models should fulfill in addition the more stringent brightness constraint of G05, there are still six models left out of which only 50% pass the Log N-Log S test.

One of the most challenging questions for the application of the test suggested in this paper is to use it next for a possible discrimination between purely hadronic compact star cooling scenarios and hybrid ones for stars having a color superconducting quark core [Grigorian et al. (2005)] which have already successfully passed the T-t test. Our conclusion is that the Log N-Log S may therefore become a powerful strategy in uncovering the properties of dense nuclear matter under the extreme conditions in neutron star interiors.

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Table 1. Properties of the selected cooling curves: A - gaps from Takatsuka & Tamagaki (2004), \(3^3\) neutron gap suppressed by 0.1; B - gaps from Yakovlev et al. (2004), \(3^3\) neutron gap suppressed by 0.1; B’ - same as for B and \(1^1\) proton gap suppressed by 0.5; B” - same as for B, \(1^1\) proton gap suppressed by 0.2 and \(3^3\) neutron gap suppressed by 0.5; C - \(T_s - T_{in}\) relation fit from BGV; D - \(T_s - T_{in}\) relation by Tsuruta (1979); E - \(T_s - T_{in}\) relation from Yakovlev et al. (2004) and \(\eta = 4 \times 10^{-6}\). The last three entries indicate whether the model complies or not with the tests: temperature-age without (wo) or with (w) the additional brightness constraint and Log N-Log S (see text and also BGV and G05 for more details).