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ROSAT X-ray sources and exponential field decay in isolated neutron stars

S. B. Popov and M. E. Prokhorov

Sternberg Astronomical Institute, Universitetskii pr.13, 119899, Moscow, Russia
e-mail: polar@xray.sai.msu.su; mike@sai.msu.su

Abstract. The influence of exponential magnetic field decay on the spin evolution of isolated neutron stars is studied. ROSAT observations have revealed several X-ray sources which may be accreting old isolated neutron stars. Assuming that this interpretation is correct, the observations can be used to constrain parameters of the exponential field decay.

We show that the range of minimum value of magnetic moment, μ_b, and the characteristic decay time, t_d, $\sim 10^{29.5} \geq \mu_b \geq 10^{28}\,\mathrm{G\,cm^3}$, $\sim 10^8 \geq t_d \geq 10^7$ yrs are excluded assuming the standard initial magnetic momentum, $\mu_0 = 10^{30}\,\mathrm{G\,cm^3}$. For these parameters, neutron stars would never reach the stage of accretion from the interstellar medium even for a low space velocity of the stars and a density of the ambient plasma. The range of excluded parameters increases for lower values of μ_0.

Key words: neutron stars – magnetic fields – stars: magnetic field – X-rays: stars – accretion

1. Introduction

Many astrophysical manifestations of neutron stars (NSs) are determined by their periods and magnetic fields. Four main evolutionary stages of isolated NSs can be singled out (see e.g. Lipunov 1992 for more detail): the *ejector*, when the star is observed as an active radio pulsar or a dead pulsar, which spins down according to magneto–dipole formula; the *propeller*, when the gravitationally captured matter is stopped near the NS magnetosphere and cannot get through the centrifugal barrier; the *accretor*, when the matter can reach the surface and the NS appears as an X-ray source; and the *georotator*, when the gravitational attraction becomes insignificant in comparison with the magnetic pressure and the NS magnetosphere interaction with the interstellar medium (ISM) is similar to the Earth magnetosphere interacting with the solar wind.

Magnetic field decay in NSs is a matter of controversy. Many models of the magnetric field decay have been proposed starting from the first simple models (Gunn & Ostriker 1970) up to the recent calculations (Sang & Chanmugam 1990, Urpin & Muslimov 1992, see also Ding et al., 1993; Jahan Miri & Bhattacharya, 1994). The strongest direct observational evidence seems to come from non-observing decay effects in radio pulsars (Lyne et al. 1998) for the exponential (or nearly exponential) decay characteristic time scales t_d shorter than $\sim 10^7$ yrs. Additional constraints for longer time scales can be obtained from comparing the properties of NS calculated by the population synthesis method with those observed in radio pulsars (see e.g. Verbunt 1994, Bhattacharya et al. 1992 and Hartman et al. 1996).

The magnetic field decay was used by Konenkov & Popov (1997) and Wang (1997) to explain properties of the source RX J0720-3125, which is considered to be a candidate for old isolated accreting NSs. If this source really represents an old accreting NS and, assuming that it was born as a normal radio pulsar (with a small period of $\ll 1$ s and a standard magnetic field of $\sim 10^{12}$ G), its properties can be explained only by field decay.

Bhattacharya et al. (1992) performed population synthesis calculations to study the field decay in single radio pulsars and came to some important conclusions about NS properties on the time scales ≥ 100 Myr. Recently the effect of the field decay in isolated NSs was studied by Colpi et al. (1998) and Livio et al. (1998).

Here we try to put some limits on the parameters of the exponential field decay assuming that some accreting X-ray sources observed by ROSAT are indeed old isolated NSs (Walter, Wolk & Neühauser 1996; Haberl et al. 1996, 1998; Neühauser & Trümper 1999; Schwope et al. 1999). There are two main possibilities for the explanation of the nature of these sources: accretion and cooling. We do not consider the possibility that all of them are normal cooling NSs or highly magnetized NSs, "magnetars" (see Neühauser & Trümper (1999) and we gave a brief discussion on this subject in Popov et al. (2000)). Cooling NSs have short lifetimes ($\sim 10^6$ yrs) in comparison with the age of a Galaxy ($\sim 10^{10}$ yrs) and thus might be relatively rare objects. Our calculations (Popov et al. 2000) show, that only for lifetimes of about 10^7 yrs, cooling NSs and accreting NSs can be observed in the solar vicinity with

Send offprint requests to: S. B. Popov: polar@xray.sai.msu.su comparable probability. Proper motion measurements are necessary to estimate spatial velocities of these candidates. High velocities (> 40-50 km/s) can exclude the accretion interpretation. However at the present time the question of interpretation is open, and one cannot exclude any variant, but we discuss here only the accretion interpretation.

On average, NSs should have high velocities due to an additional kick obtained during the supernova explosion (Lyne and Lorimer 1994, Lorimer et al. 1997). The ISM accretion rate for high velocity objects should be rather low. However, recent population synthesis calculations (Popov et al. 2000) indicate that several old accreting NSs can be observed in the solar vicinity even for the space velocity distribution similar to one that has been derived from radio pulsar observations. And since there is the theoretical possibility of accreting isolated NSs, we wish to discuss how they can be used (possibly in the future) to put some limits on the models of field decay.

2. Calculations and results

The main idea is to calculate the ejector time, t_E, i.e. a time interval spent by an INS on the ejector stage, for different parameters of the field decay and using standard assumptions for the initial NS parameters, and to compare this time with the Hubble time, t_H.

The ejector time, t_E, monotonically increases with increasing velocity of NS v and density of the ISM n. For a constant NS magnetic field this relation takes the simple form:

$$t_E(\mu = const) \sim 10^9 \mu_{30}^{-1} n^{-1/2}\, v_{10}\, \mathrm{yrs}. \quad (1)$$

Using a high mean ISM density $n \sim 1\mathrm{cm}^{-3}$ and a low space velocity of NSs (about the sound speed), $v \sim 10\,\mathrm{kms}^{-1}$, we arrive at the lower limit of t_E. Any other value of density and velocity should increase t_E (these quantities in fact are not independent since only low-velocity NSs remain for a long time inside the galactic disc where such high ISM density is observed). After the ejection stage has been over, the NS passes to the propeller stage and only after that can become an accreting X-ray source. The duration of the propeller stage t_P is poorly known (e.g. for a constant magnetic field t_P is always less than t_E, see Lipunov and Popov 1995, for a decaying field these timescales can be comparable). Therefore if for some parameters of an INS the lower limit of t_E exceeds the Hubble time $t_H \simeq 10^{10}$ yrs, it can not come to the accretion stage and hence can not underlie the ROSAT X-ray source.

In addition, we assumed that NSs are born with sufficiently small rotational periods p_0 and have the same parameters of the magnetic field decay. We shall consider different initial surface magnetic field values. The field decay is assumed to have an exponential shape:

$$\mu = \mu_0 \cdot e^{-t/t_d},\ for\, \mu > \mu_b \quad (2)$$

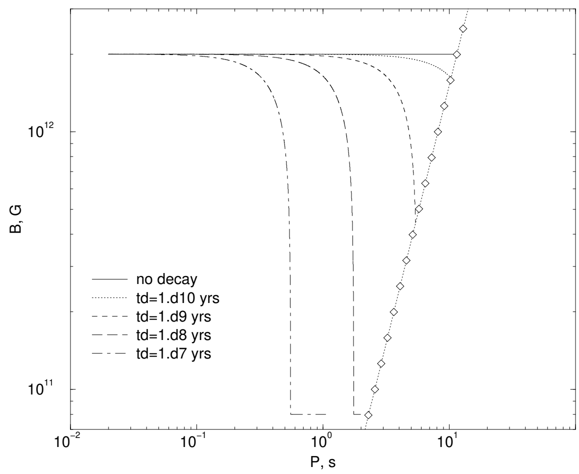

Fig. 1. Tracks on P-B diagram. Tracks are plotted for bottom polar magnetic field $8 \cdot 10^{10}$ G, initial polar field $2 \cdot 10^{12}$ G, NS velocity $10\,\mathrm{kms}^{-1}$, ISM density $1\,\mathrm{cm}^{-3}$ and different t_d. The last point of tracks with different t_d corresponds to the following NS ages: 10^{10} yrs for $t_d = 10^7$ and $t_d = 10^8$ yrs; 1.5×10^9 yrs for $t_d = 10^9$ yrs; $\sim 2 \cdot 10^9$ yrs for $t_d = 10^{10}$ yrs. The initial period is assumed to be $p_0 = 0.020$ s. The line with diamonds shows the ejector period, p_E.

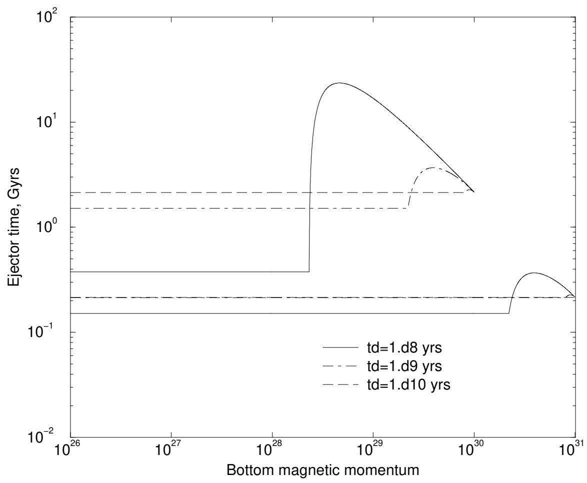

Fig. 2. Ejector time t_E (in billion years) vs. the bottom value of the magnetic momentum. The curves are shown for two values of the initial magnetic momentum: $10^{30}\,\mathrm{G\,cm}^3$ (upper curves) and $10^{31}\,\mathrm{G\,cm}^3$.

where μ_0 is the initial magnetic moment ($\mu = \frac{1}{2} B_p R_{NS}^3$, here B_p is the polar magnetic field, R_{NS} is the NS radius), t_d is the characteristic time scale of the decay, and μ_b is the bottom value of the magnetic momentum which is reached at the time

$$t_{cr} = t_d \cdot \ln\left(\frac{\mu_0}{\mu_b}\right) \tag{3}$$

and does not change after that.

In Fig. 1 we show as an illustration the evolutionary tracks of NSs on $P - B$ diagram for $v = 10\,\mathrm{km\,s^{-1}}$ and $n = 1\,\mathrm{cm^{-3}}$. Tracks start at $t = 0$ when $p = 20\,\mathrm{ms}$ and $\mu = 10^{30}\mathrm{G\,cm^3}$ and end at $t = t_H = 10^{10}$ yrs (for $t_d = 10^9$yrs, $t_d = 10^{10}$ yrs and for a constant magnetic field) or at the moment when $p = p_E$ (for $t_d = 10^7$ yrs and $t_d = 10^8$ yrs). The line with diamonds shows $p = p_E(B)$.

Since the accretion rate from the ISM is generally very small (even for our parameters), less than $\sim 10^{12}\,\mathrm{g\,s^{-1}}$, no influence of the accretion on the field decay was taken into account (see Urpin et al., 1996).

The ejector stage ends when the critical ejector period p_E is reached:

$$p_E = 11.5\,\mu_{30}^{1/2} n^{-1/4} v_{10}^{1/2}\,\mathrm{s}, \tag{4}$$

where $v_{10} = \sqrt{v_p^2 + v_s^2}/10\,\mathrm{km\,s^{-1}}$. v_p is the NS space velocity, v_s and n are the sound velocity and density of the ISM, respectively. In the estimates below we shall assume $v = 10$ km s^{-1} and $n = 1$ cm^{-3}.

The initial NS spin periods should be taken much smaller than p_E. To calculate the duration of the ejection stage here we assume $p_0 = 0$ s. The actual value of p_0, if much less than p_E, has no effect on our results, i.e. t_E is determined only by p_E and the history of the field decay. We used the magnetodipole formula to compute this time, which in fact is appropriate for quite different specific ways of NS rotational energy loss (see Beskin et al. 1993 for a review):

$$\frac{dp}{dt} = \frac{2}{3}\frac{4\pi^2\mu^2}{pIc^3}, \tag{5}$$

where μ can be a function of time.

After a simple calculation we arrive at the following expression for t_E:

$$t_E = \begin{cases} -t_d \cdot \ln\left[\frac{T}{t_d}\left(\sqrt{1+\frac{t_d^2}{T^2}} - 1\right)\right], \; t_E < t_{cr} \\ t_{cr} + T\frac{\mu_0}{\mu_b} - t_d\frac{1}{2}\left(\frac{\mu_0}{\mu_b}\right)^2\left(1 - e^{-2t_{cr}/t_d}\right), \\ \qquad\qquad\qquad t_E > t_{cr} \end{cases} \tag{6}$$

where the coefficient T (which would be simply t_E for $\mu = \mu_0 = const$) is determined by the formula:

$$T = \frac{3Ic}{2\mu_0\sqrt{2v\dot{M}}} \simeq 10^{17} I_{45} \mu_{0_{30}}^{-1} v_{10}^{-1/2} \dot{M}_{11}^{-1/2}\,\mathrm{s}. \tag{7}$$

Here $\dot{M}$ can be formally determined according to the Bondi equation for the mass accretion rate even if the NS is not at the accretion stage:

$$\dot{M} \simeq 10^{11}\, n v_{10}^{-3}\,\mathrm{g\,s^{-1}}. \tag{8}$$

The results of calculations of t_E for several values of μ_0 and t_d are shown in Fig. 2. The right end points of all curves are limited by the values $\mu_b = \mu_0$. These points correspond to the evolution of an INS with constant magnetic field (see Eq. (2)) and for them $t_E = T$. If μ_b is small enough, the NS field has no time to reach the bottom value. In this case t_E is determined by the 1st branch by Eq. (6) and does not depend on μ_b. In the Fig. 2 this situation corresponds to the left horizontal parts of the curves. At

$$\mu_b > \mu_0\left[\frac{T}{t_d}\left(\sqrt{1 - \frac{t_d^2}{T^2}} - 1\right)\right]$$

the situation changes so that t_E starts depending on μ_b. In this region two counter-acting factors operate. On the one hand, the NS braking becomes slower with decreasing μ (see Eq. (5)). On the other hand, the end period of the ejection p_E becomes shorter (4). Since $t_E < T$ at the left hand side horizontal part and $(dT_E/d\mu_b)|_{\mu_0} < 0$, the right hand side of the curve must have a maximum. The first factor plays the main role to the right of the maximum, the magnetic field there rapidly falls down to μ_b at $p \ll P_E$ and most often NS evolves with the minimum field $\mu = \mu_b$ (this time increases with decreasing μ_b). To the left of the maxium but before the horizontal part the NS magnetic field reaches $\mu = \mu_b$ with the spin period close to p_E (the smaller μ_b, the closer) and soon after $t = t_{cr}$, the NS leaves the ejection stage.

As seen from Fig. 2 , for some combination of parameters, t_E is longer than the Hubble time. It means that such NSs never evolve further than the ejector stage.

We argue that if the soft ROSAT X-ray sources are accreting isolated neutron stars, the combinations of t_d and μ_b for which no accreting isolated NS appear, can be excluded for their progenitors. The regions of excluded parameters are plotted in Figs. 3 and 4.

The hatched regions correspond to parameters for which t_E is longer than 10^{10} yrs, so an INS with such parameters never reaches to the accretor stage and hence cannot appear as an accreting X-ray source. In view of observations of accreting old isolated NSs by ROSAT satellite, this region can be called "forbidden" for selected parameters of the exponential field decay with a given μ_0.

In the "forbidden" region in Fig. 3, which is plotted for $\mu_0 = 10^{30}\,\mathrm{G\,cm^3}$, all NSs reach the bottom field in a Hubble time or faster, and the evolution at late stages proceeds with the minimal field. The left hand side of the forbidden region is determined approximately by the condition

$$p_E(\mu_b) = p(t = t_{cr}). \tag{9}$$

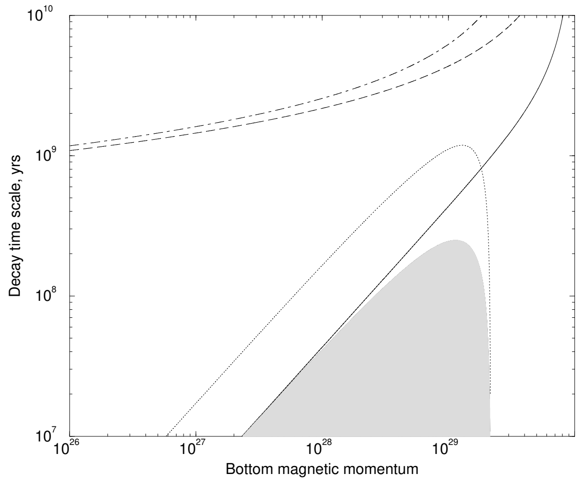

Fig. 3. The characteristic time scale of the magnetic field decay, t_d, vs. bottom magnetic moment, μ_b. In the hatched region t_E is greater than 10^{10}yrs. The dashed line corresponds to $t_H = t_d \cdot \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ years. The solid line corresponds to $p_E(\mu_b) = p(t = t_{cr})$, where $t_{cr} = t_d \cdot \ln(\mu_0/\mu_b)$. Both the lines and hatched region are plotted for $\mu_0 = 10^{30}\,\mathrm{G\,cm^{-3}}$. The dash-dotted line is the same as the dashed one, but for $\mu_0 = 5 \cdot 10^{29}\,\mathrm{G\,cm^3}$. The dotted line shows the border of the "forbidden" region for $\mu_0 = 5 \cdot 10^{29}\,\mathrm{G\,cm^3}$.

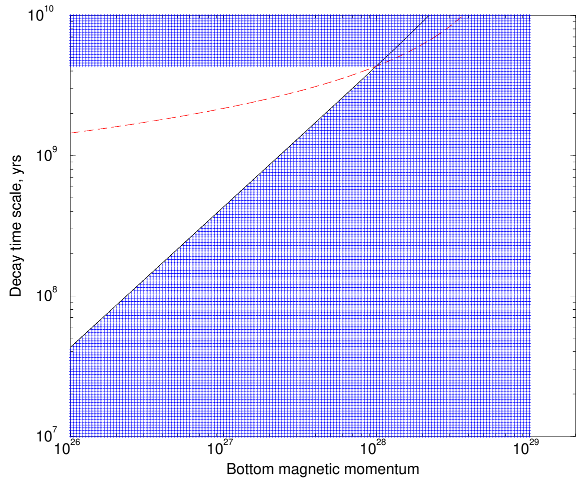

Fig. 4. The characteristic time scale of the magnetic field decay, t_d, vs. bottom magnetic momentum, μ_b. In the hatched region t_E is greater than 10^{10} yrs. The dashed line corresponds to $t_H = t_d \cdot \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ yrs. The solid line corresponds to $p_E(\mu_b) = p(t = t_{cr})$, where $t_{cr} = t_d \cdot \ln(\mu_0/\mu_b)$. Both lines and region are plotted for $\mu_0 = 10^{29}\,\mathrm{G\,cm^{-3}}$.

A small difference between the line corresponding to the above condition and the left hand side of the "forbidden" region appears because a NS can slightly change its spin period even with the minimum magnetic moment $\mu = \mu_b$. However due to a small value of the field the angular momentum, losses are also small.

The right hand side of the region is roughly determined by the value of μ_b, with which an INS can reach the ejector stage for any t_d, i.e. this μ_b corresponds to the minimum value of μ_0 with which a NS reaches the ejector stage without field decay.

NSs to the right from the "forbidden" region leave the ejector stage, because the bottom magnetic momentum there is relatively high so that the spin-down is fast enough throughout the ejector stage. To the left of the "forbidden" region the situation is different. The NS spin-down is very small and they leave the ejector stage not because of the spin-down, but due to a decrease in p_E, which depends upon the magnetic moment.

In Fig. 3 the "forbidden" region is also shown for $\mu_0 = 0.5 \cdot 10^{30}\,\mathrm{G\,cm^3}$ (dotted line). The dashed line in Fig. 3 shows that for all interesting parameters an INS with $\mu_0 = 10^{30}\,\mathrm{G\,cm^3}$ reaches μ_b in less than 10^{10} yrs. The dash-dotted line shows the same for $\mu_0 = 0.5 \cdot 10^{30}\,\mathrm{G\,cm^3}$. The solid line corresponds to $p_E(\mu_b) = p(t = t_{cr})$, where $t_{cr} = t_d \cdot \ln(\mu_0/\mu_b)$. The physical sense of this line can be described in the following way. This line divides two regions: in the upper left region t_d are relatively long and μ_b relatively low, so the NS cannot reach the bottom field during the ejector stage; in the lower right region t_d are short and μ_b relatively high, so the NS reaches μ_b at the stage of ejection.

Fig. 4 is plotted for $\mu_0 = 10^{29}\,\mathrm{G\,cm^3}$. For long t_d ($> 4 \cdot 10^9$ yrs) the NS cannot leave the ejector stage for any $\mu_b \leq \mu_0$. This is the reason why in the upper part of the figure a horizontal "forbidden" region appears.

3. Discussion and conclusions

We tried to evaluate the region of parameters which are excluded for models of the exponential magnetic field decay in NSs using the possibility that several ROSAT soft X-ray sources are indeed old accreting isolated NSs in X-rays. Of course we are not absolutely sure that all of the observed candidates are accreting NSs. Some of them can be cooling NSs or magnetars (this appears plausible, for example, for the source RX J0720-3125 as it has a spin period similar to soft gamma-ray repeaters). Future observations (especially the proper motion and $\dot{p}$ measurements) are required.

The intermediate values of t_d ($\sim 10^7 - 10^8$ yrs) in combination with the intermediate values of μ_b ($\sim 10^{28} - 10^{29.5}\,\mathrm{G\,cm^3}$) for $\mu_0 = 10^{30}\,\mathrm{G\,cm^3}$ can be excluded for progenitors of isolated accreting NSs because NSs with such parameters would always remain on the ejector stage and never pass to the accretion stage. Even if all modern candidates are not accreting objects, the possibility of limitations of magnetic field decay models based on future observations of isolated accreting NSs should be addressed.

As seen in Fig. 2, for higher μ_0 NSs should reach t_E even for $t_d < 10^8$ yrs, for weaker fields the "forbidden" region becomes wider. The results are dependent on the initial magnetic field μ_0, the ISM density n, and NS velocity v. So here different ideas can be investigated. For example, this implies that the observed accreting isolated NSs can come from objects with a high initial magnetic field, and the others never appear as accreting objects because their parameters lie in the forbidden region. To explore this idea in details, the population synthesis of NSs for realistic distributions of v, μ_0 and n is needed. It is clear, however, that accreting old isolated NSs can hardly be formed from the initially high-field objects because the fraction of the high-field NSs cannot be large (as follows from radio pulsars observations). Since the fraction of the low velocity NSs is not more than several percent (Popov et al. 2000) and the volume fraction filled with relatively high density ISM is also small, accreting old isolated NSs should come from the "typical" population, i.e. from NSs with μ_0 about $10^{30}\,\mathrm{G\,cm}^3$.

In fact the limits obtained are even stronger than they could be in nature, because we did not take into account that NSs can spend some significant time (in the case with field decay) at the propeller stage (the spin-down rate at this stage is very uncertain, see the list of formulae, for example, in Lipunov & Popov 1995 or Lipunov 1992). The calculations of this effect for different models of non-exponential field decay will be studied separately.

We cannot derive parameters of the field decay in accreting NSs in close binaries, because there the situation is completely different due to high accretion rates that can significantly affect the process of magnetic field decay. So our results cannot be applied to millisecond radio pulsars or other objects which were formed in close binary systems.

Note that there is another reason for which a very fast decay down to small values of μ_b can also be excluded, because this would lead to a huge amount of accreting isolated NSs in drastic contrast with observations. This situation is similar to the "turn-off" of the magnetic field of an INS (i.e., quenching any magnetospheric effect on the accreting matter). So for any velocity and density distributions we should expect significantly more accreting isolated NSs than we know from ROSAT observations (of course, for high velocities X-ray sources will be very dim, but close NSs can be observed even for velocities ~ 100 km s^{-1}).

We conclude that the existence of several old isolated accreting NSs observed by ROSAT (if it is the correct interpretation of observations), can put important bounds on the models of the magnetic field decay for isolated NSs (without influence of accretion, which can stimulate field decay). These models should explain observations of ~ 10 accreting isolated NSs in the solar vicinity. Here we can not fully discuss the relations between decay parameters and X-ray observations of isolated NSs without detailed calculations. What we showed is that this connection should be taken into account and made some illustrations of it, and future investigations in that field RE desirable.

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