Do Young Neutron Stars Which Show Themselves As AXPs, SGRs and Radio Pulsars Accrete?

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Abstract. We examined the fall-back disk models, and in general accretion, proposed to explain the properties of anomalous X-ray pulsars (AXPs), soft gamma repeaters (SGRs), and radio pulsars (PSRs). We checked the possibility of some gas remaining around the neutron star after the supernova explosion. We also compared AXPs and SGRs with X-ray pulsars in X-ray binaries. We conclude the existing theory of accretion from a fall-back disk is insufficient to explain the nature of AXPs/SGRs, particularly the SGR bursts. We also discussed the proposed model of combination of dipole radiation and propeller torques in order to explain the evolution of radio pulsars on the P-P diagram. The predictions of this model contradict the observational data.

Key words. AXP – SGR – PSR

1. Introduction

In the last few years soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs), which are considered as a separate class of X-ray pulsars, have attracted much attention (see Mereghetti 2001 and references therein). The only important difference between SGRs and AXPs is that SGRs have active periods showing gamma ray bursts. It is claimed that SGRs and AXPs are very young (~10^4 yrs), isolated neutron stars (NS) with very high magnetic fields. A puzzling property of these objects is that their X-ray luminosities (L_x) are 1-3 orders of magnitude higher than their rate of rotational energy loss (E). Besides, repeating gamma ray bursts of SGRs is the most important property of this class of objects. In order to explain the main physical peculiarities of these objects, not only a theory overstepping the limits of the standard NS/pulsar physics is needed, but also examining another type of NS, known as radio quiet NS with low X-ray luminosity is required.

There is no radio radiation detected from AXPs/SGRs, only the upper limits for radio fluxes (and luminosities) are known. It does not necessarily mean that these objects do not radiate in the radio band only because of failing to observe radio pulses, because most of the pulsars are born with low luminosities (Lyne et al. 1998; Allahverdiev et al. 1997) and also because of the beaming factor. However, if somehow it is shown that there is no radio radiation from AXPs and SGRs, then there will be a sharp drop in the radio luminosity of pulsars including AXPs and SGRs as we go to higher magnetic fields. But it is difficult to check this possibility because it is not easy to increase the number of such observational data as the number of AXPs and SGRs are small and they are located at large distances.

The so called magnetar model is proposed by Thompson and Duncan (1995) as a potential explanation for the nature of AXPs and SGRs. According to this model these sources are isolated rotating NSs with surface dipole magnetic fields of 10^{14}-10^{15} G, extracting their luminosity from the decay of the magnetic field.

The alternative model is that the X-ray luminosity is due to accretion from a fall-back disk that is left over from the supernova that formed the NS (Chatterjee et al. 2000; Alpar 2001). In this work we will show the incompetence of the accretion theory in explaining the AXP/SGR, and also radio pulsar properties.

2. Bursts and Flares Due to Magnetic Activities

In general bursts, and in particular gamma-ray bursts, are common astronomical phenomena. These are observed, for instance, for the Sun, flare stars (UV-Cet type), and T-Tauri stars. Flares have fast rise-times of luminosity and longer decay times. For all of the flaring objects, the flares are related to the magnetic activities and have short char-
acteristic times (~minutes for UV-Cet stars). Large flares are followed by smaller ones. Durations of SGR bursts bear resemblance to (taking into account the very small size of the NS) durations of flares, 10 ms-10 s. The difference between flares and SGR bursts is the power output, and time intervals between the strong flares (for UV Cet stars it is, on the average, about 10-100 times shorter compared to SGR bursts). The ratio of the energy of outburst to the persistent radiation energy for flare stars (UV-Cet type) can be as large as $10^4$ and for SGRs $10^8$. Since AXPs and SGRs are considered as one class of objects, we must enquire if AXPs also have outbursts, however, infrequently and with low intensity.

SGR bursts have very large energies in the range $\sim 10^{40-44}$ erg with characteristic timescales of 10 ms-10 s. Such bursts can not be brought into existence by the suggested accretion onto a NS models and they have never been observed in accreting binary systems even though X-ray luminosities of some binaries are about two orders of magnitude higher than the persistent X-ray radiation of AXPs and SGRs. It must be noted that, the X-ray bursts in low mass X-ray binaries (LMXBs) are due to thermonuclear reactions on the surfaces of old NSs (Lipunov 1992). These bursts, which have very different physical mechanisms, do not have a relation with the magnetar models.

3. The Fall-Back Disk Model

3.1. Can a Disk Remain Around a Neutron Star After Supernova Explosion?

In suggested accretion models, SGR bursts can not be easily explained. However, magnetar models have the potential to explain the gamma-ray bursts as well as other properties of AXPs and SGRs like the persistent X-ray luminosity. The compactness of the values of $L_x$ is achieved due to the fact that the parameters $\dot{M}$ and $B$ are adjustable in a wide range in the accretion models.

In the fall-back disk model, it is very important to know how much mass of gas may remain close to the NS after the Supernova explosion. Gravitational energy of a NS with one $M_\odot$ and a radius about 1.5×$10^6$ cm can be estimated as $(1-2)\times 10^{53}$ ergs which is about 5-10% of $M_\odot c^2$. The gravitational energy is converted into heat and rotational energy, and this heating energy, about $10^{53}$ ergs, transforms into the energy of neutrinos and antineutrinos during supernova explosion (Zeldovich and Guseinov 1965, Guseinov 1966). From the study of SNRs, it is known that their kinetic energies lie in the interval $3 \times 10^{49} - 10^{51}$ ergs. The well known kinetic energy of the Crab SNR approximately gives the lower boundary for kinetic energy for SNRs. From the observations of SNe it is known that the explosion energy, on the average, lies in the interval $10^{50}-10^{51}$ ergs and the thrown out mass of gas is $\sim (0.5-6)M_\odot$. A large mass outflow took place in SNR Cassiopeia A, $\approx 4M_\odot$ (Vink et al. 1998). This shows that only a small part of the energy of the neutrinos transform into explosion energy and in principle this is enough to sweep out all the mass which are present near the NS. On the other hand, whether some fall-back matter remain near the neutron star (and also its quantity) depends on the velocity distribution of the thrown out matter.

The part of the gravitational energy which is transformed into rotational energy of the NS mainly depends on initial value of angular momentum (and its distribution) of the collapsed star. Even if we know these values, in order to calculate the rotational energy of the NS we must also know the value of the magnetic viscosity as well as the dynamics of the collapse and the explosion. At this point, there are many uncertainties and therefore angular momentum and rotational energy for the NS must be estimated from the initial period of pulsars. Since this period is about 10 ms, initial rotational energy of the NS must be about $5 \times 10^{51}$ ergs. The collapse transforms the angular momentum from the NS being born to external parts and this can sweep out the surrounding matter (Bisnovaty-Kogan 1971; Amnuel et al. 1973). Actually, observational data do not show presence of gaseous disks or planets near single pulsars with a magnetic field in excess of $10^{10}$ G. Therefore there is no basis for the presence of any matter of fall-back around AXPs and SGRs, but we can not completely exclude the possibility of a little bit of gas remaining near the neutron star.

3.2. Are AXPs and SGRs Accreting Systems?

When the collapse begins to slow down, the SN explosion occurs and the shell around the NS is thrown away. Due to conservation of angular momentum, the rotational speed of the shell will decrease as it moves away from the NS. At the beginning the magnetic field of the NS is frozen to the shell. This slows down the NS, and speeds up the shell (Bisnovaty-Kogan 1971 and Amnuel et al. 1973). Angular speed of the shell falling back increases. Consequently, the NS will be spun-up by the fall-back matter if the propeller mechanism is not working, i.e. if the fall-back matter does not lose angular momentum. However, accretion from a fall-back disk models do not explain how the fall-back disk loses angular momentum instead of gaining it.

Moreover, the production mechanism of fall-back matter do not exist in the accretion models trying to explain AXPs and SGRs. We do not know how much amount of mass and how much momentum there is in a fall-back disk. The parameters of the disk (related to the magnetic field and rotational speed of NS) is chosen such that the X-ray luminosity is about $10^{34-36}$ erg/s and $P \approx 10^{-13} - 10^{-11}$ s/s. So this model in fact is not related to the properties and history of the fall-back matter. On the other hand, the only accretion model (onto a $10^{12}$ G NS) which takes into account the small ages of AXPs and SGRs is the model of accretion from a fall-back disk.
4. Comparisons Between AXPs/SGRs and X-ray Pulsars in Binaries

We examined the differences between the $L_x/|E|$ values of AXPs, SGRs, and X-ray pulsars in binary systems. Here, $L_x$ is the X-ray luminosity which depends only on the rate of accreted mass, $M_x$ (apart from NS' own parameters) and $E$ is the rate of rotational energy change which depends on both $M_x$ and specific angular momentum, ($L_{spc}$). Therefore, $L_x/|E|$ will be inversely proportional to $L_{spc}$. In Table 1, $L_x$ and $|E|$ values (and their ratio) of X-ray pulsars in high mass X-ray binaries (HMXBs), a LMXB, and AXPs/SGRs with known $P$ values are displayed (we do not include transient X-ray binaries in this table, because it is difficult to determine the correct value of $L_x/|E|$ for such systems). For HMXBs, $L_x/|E|$ values range from $3 \times 10^3$ to $3 \times 10^6$, with one exception, namely H0115-737, which has a lower $L_x/|E|$ value of 65. This is because of the small spin period value of this pulsar. For LMXBs, we expect $L_x/|E|$ values to be less than those of HMXBs because there is disk accretion in LMXBs so that $L_{spc}$ must be higher than those of HMXBs which have predominantly wind accretion. There is only 1 LMXB with reliable $P$ and $L_x$ values and its $L_x/|E|$ value is $(5-7.5) \times 10^2$, less than all of the $L_x/|E|$ values of HMXBs which have spin periods close to spin periods of AXPs and SGRs. If there is a fallback disk for AXPs/SGRs which are assumed to be single stars, we expect $L_{spc}$ to be less than or equal to $L_{spc}$ of HMXBs. However, for only 3 AXPs $L_x/|E|$ value is greater than that of the LMXB but considerably smaller than for HMXBs with similar spin periods. This contradicts the suggested fallback disk models.

Accretion onto a NS can spin it up or down. However, for binary systems with the same parameters, we expect that as $M_x$ increases $P$, $|E|$ and $L_x$ increase. There is disk accretion in LMXBs and unit mass of the accreted matter has more angular momentum compared to the unit mass of the accreted matter in HMXBs since, on the average, they have higher orbital velocity. Because of this reason, for LMXBs $L_x/|E|$ is smaller than for HMXBs, on the average. Without the propeller effect, value of $L_x/|E|$ for fallback matter accreted onto the NS must not be smaller than for X-ray pulsars in HMXBs if their spin period values are close to each other. As seen from Table 1, 4 of 7 AXPs/SGRs seem to have lower values than LMXBs that accretion from fallback matter without propeller effect contradicts the observational data. On the other hand, the propeller effect must be very weak in the plerionic part of the interiors of the shell, because SNRs which have genetic connections with AXPs have pure shell type structures.

LMXBs, like HMXBs, show transient (T) characteristics as well as quasi-periodic oscillations (QPOs) and bursts (B). These characteristics increase as the binary separation decreases (when the disk is closer to the NS). In AXPs no such properties, or any other binary characteristics are observed.

5. The Other Aspects of Accretion: Single Stars

Classical accretion onto a single star theory is a very developed and well known subject in astrophysics. To explain the radiation from stars, in early times accretion from interstellar medium and contraction of stars were proposed. Later it was understood that thermonuclear reactions in the cores of stars are the source of radiation of stars, then there was no need for accretion anymore. On the contrary, it was found that stars have winds, sometimes very strong winds.

Salpeter (1964) tried to explain the X-ray sources (when they were first found by Giacconi et al. 1962) based on accretion from interstellar medium onto a single neutron star. So accretion onto single stars theory was called to mind. It is well-developed for systems including NSs and black holes. However, accretion from interstellar medium is found to be wrong, because it is found that if there is accretion onto a single NS, then the NS becomes hotter and the speed of sound in the surrounding matter increases, so that the accretion rate decreases by 6 (Schwartzman 1970) or 8 (if the magnetic field frozen in the interstellar medium is also taken into account, Amnuel and Guseinov 1972) orders of magnitude. X-ray sources were explained as accreting binary systems (Zeldovich and Guseinov 1966).

After PSRs were discovered, it was understood that rapidly rotating single NSs also produce winds (Pacini 1967). Such winds are much more efficient than radiation pressure in sweeping up the surrounding matter around PSRs (Lipunov 1992). Then accretion theory could only work for slowly rotating single NSs with low magnetic fields. For 30 years, it has been searched for accreting old single NSs in optical and soft X-ray bands without considerable success (Danner 1998). Also there were no success in finding fluctuating accreting (from interstellar medium) single black holes (Schwartzman 1970). There is no sign of fallback matter in the central parts, particularly in the near-environments of point sources of historical SNRs Crab (PSR J0534+2200), 3C58 (RX J0201.8+6435, Torii et al. 2000; Bocchino et al. 2001), Cas A (CXO J2323+5848, McLaughlin et al. 2000; Kaplan et. al 2001).

5.1. Propeller Mechanism for Radio Pulsars

Alpar et al. (2001) following Menou et al. (2001) have proposed that the distribution of radio pulsars in $P - \dot{P}$ diagram can be explained by the combination of dipole torque and propeller torque of a fall-back disk. Their model predicted the evolutionary tracks of pulsars in the $P - \dot{P}$ diagram as shown in Figure 1. According to Peng et al. (1982) and Huang et al. (1982) neutrino emission from pulsars and magnetic dipole radiation of superfluid neutrons, respectively, also yield similar tracks. Down to a minimum period derivative value the pulsars follow dipole-dominant radiation tracks and after that point propeller torques dominate and period derivative becomes $\dot{P} \propto P^3$. After the dipole-dominant phase is over, the ages predicted by the model of Alpar et al. (2001) and the characteristic
ages follow different paths as can be seen in Figure 1. The real ages of pulsars are the kinematic ages which are valid for all models. The kinematic age is proportional to the distance of the PSR from the Galactic plane. So, the propeller model can be tested by comparing the model’s age predictions and kinematic ages. Then, the older pulsars must lie in the upper right corner part of the $P - \dot{P}$ diagram according to the propeller model, and these pulsars must be far away from the Galactic plane. In order to check this, we constructed the $P - \dot{P}$ diagram by representing the pulsars with $|z|$ coordinates $< 200$ pc with + symbol and the pulsars with $|z|$ coordinates $> 400$ pc by open circles in Figure 1.

In general, the birth places of pulsars are very close to the Galactic plane. The average scale height at the time of birth is about 60 pc, similar to OB stars. However, in the outer parts of the Galaxy, the star formation regions may deviate from the geometric plane of the Galaxy. Optical observations of cepheids with high luminosities and of red supergiants located at distances about 5-10 kpc from the Sun, in the direction $l \sim 200^\circ - 330^\circ$, showed that the star formation regions are located below the Galactic plane by about 300pc, and the star formation regions in the direction $l \sim 70^\circ - 100^\circ$ are located above the plane by about 400pc. The star formation regions at about 3-5 kpc from the Sun in the direction $l \sim 270^\circ - 320^\circ$ are located about 150 pc below the geometric plane of the Galaxy (Berdnikov 1987). These deviations of the locations of star formation regions from the Galactic plane have strong influence on the kinematic ages of young pulsars. We did not include the pulsars located in the deviated parts of the star formation regions indicated above. We also did not include the pulsars beyond 5 kpc due to large uncertainties in the distance measurements. As seen from Figure 1, along the path of the dipole+propeller tracks, kinematic ages first increase then start to decrease. This is inconsistent with the propeller model. A few of the pulsars with characteristic ages less than 10$^6$ years, are more than 400pc away from the plane which may be related to their birth places being high above the Galactic plane (the progenitor can be a runaway star) and their speed being large.

Pulsars with small periods and high period derivatives (upper left region of the $P - \dot{P}$ diagram) are found to be connected to SNRs (Allakhverdiev et al. 1997; Kaspi 2000). This shows that those pulsars are very young. Pulsars evolve roughly with constant magnetic field: the number of pulsars increase with characteristic time on constant magnetic field lines as can be seen in Figure 1. It is unclear how the model given in Alpar et al. (2001) explains the distribution of pulsars in the $P - \dot{P}$ diagram. The magnetic dipole evolutionary tracks are more reliable (Allakhverdiev & Tagieva 2002).

There is also another possibility to test the propeller model of Alpar et al. (2001) which predicts the change of $\dot{P}$ ($\ddot{P}$) to be the highest on the propeller-dominant parts of the evolutionary tracks. In order to find the braking index ($n = \Omega / \dot{\Omega}^2$, where $\Omega$ is the angular frequency of the pulsar) the value of $\dot{P}$ must be large. About 40 years of observations have shown that, in that part of the diagram, $\dot{P}$ values of pulsars are not large enough to be measured. This also contradicts the propeller model.

Glitch is a common phenomenon for young radio pulsars. According to the model of Alpar et al. (2001) for pulsars with $P > 1$ s and $\dot{P} > 10^{-14}$ s/s no glitches must be observed because according to their model these pulsars must be older than about 10$^7$ yrs. If glitches from these pulsars are observed then this will directly show that they are young.

6. Conclusions

As shown in section 2, fall-back matter cannot increase the rotation period of NS if we do not consider the propeller effect to be working with accretion. On the other hand, the propeller effect, if there is any, must be very weak in the plerionic parts, because SNRs which have genetic connections with AXPs have pure shell type structures.

Ratio of the X-ray luminosity to the rate of rotational energy loss of the accreting matter ($L_x / |\dot{E}|$) of AXPs/SGRs have values on the average several orders of magnitude smaller than that of X-ray pulsars in HMXBs with similar spin periods. Therefore the unit accreted mass in AXPs/SGRs have the highest value of angular momentum. This contradicts the fact that AXPs/SGRs are not close binary systems. For AXPs/SGRs to have the largest angular momentum, there must be strong propeller effects on them. Is it possible that both accretion and propeller effects work together?

Fall-back disk models do not consider formation and source of the fall-back matter. They choose free parameters for the disk around the NS to have the necessary values of $P$, $\dot{P}$, and X-ray radiation. Fall-back matter models should include the propeller mechanism and also some additional tools to explain the SGR phenomenon. Otherwise, magnetar models are better in order to explain the nature of AXPs and particularly SGRs.

In section 3, we have seen that the explanation of the $P - \dot{P}$ diagram by fall-back disks around pulsars is not satisfactory. Simple accretion theories are in general not fruitful when applied to young and fastly rotating NSs.

References

Allakhverdiev, A.O., Guseinov, O.H. & Tagieva, S.O., 1997, Astronomy Letters, 23, 628
Allakhverdiev, A. O. & Tagieva, S. O., 2002, will be published in Astronomical and Astrophysical Transactions Alpar, M.A., 2001, ApJ, 554, 1245
Alpar, M.A., Ankay, A. & Yazgan, E., 2001, ApJL, 557, 61
Amnuel, P. R. & Guseinov, O. H., 1972, Astron. Nach. Bd. 294, 139
Amnuel, P.R., Guseinov, O.H., & Kasumov, F.K., 1973, Sov. Ast., 16, 932
Angelini L., White, N. E., Nagase, F., et al., 1995, ApJ, 449, L41
Baykal, A. & Swank, J., 1996, ApJ, 460, 470
Bisnovaty-Kogan, G., 1971, Sov. Ast. 14, 652
## Table 1. The Data of AXPs/SGRs, and Pulsars in X-ray Binaries with Measured $\dot{P}$ Values

| Names          | $P_{\text{orb}}$ (d) | $P$ (s) | $\dot{P}$ $10^{-11}$ (s/s) | $L_\text{x}$ $10^{36}$ (erg/s) | $|\dot{E}| = 3.9410^{78} \frac{|\dot{P}|}{P^2}$ (erg/s) | $L_\text{x}/|\dot{E}|10^{3}$ | Ref. |
|----------------|----------------------|--------|--------------------------|--------------------------------|-------------------------------------------------|-------------------------------|-----|
| H053109-6609.2 | $\sim 700$           | 13.68  | 3.7                      | 2.4                            | 5.7                                             | 5 − 20                         | [1, 2, 3] |
| T              | (0.1 − 2.4)          |        |                          |                                 |                                                 |                               |     |
| LMC            | (2 − 10)             |        |                          |                                 |                                                 |                               |     |
| H0532-664      | 1.41                 | 13.5   | 6.1                      | 400                            | 10                                             | 400                            | [4, 5, 15, 16] |
| L1627-673      | 0.029                | 7.67   | 17                       | 2                              | 44                                             | 0.5 − 0.75                     | [8, 9, 10] |
| Q              | (2 − 10)             | 0.033  |                          |                                 |                                                 |                               |     |
| H1119-603      | 2.09                 | 4.82   | −3.8                     | 111                            | 140                                            | 3                             | [6, 7, 20] |
| Q              | (2 − 10)             | 0.033  |                          |                                 |                                                 |                               |     |
| H0115-737      | 3.89                 | 0.71   | −1.6                     | 10130                          | 0.065                                          |                               | [17, 18, 19] |
| SMC            | (2 − 10)             | 0.033  |                          |                                 |                                                 |                               |     |
| H0352+309      | 580.7                | 836.8  | 420                      | 0.006                          | 0.0029                                         | 20                            | [11, 12, 13, 14] |
|                | (0.1 − 2.4)          |        |                          |                                 |                                                 |                               |     |
| H1538-522      | 3.73                 | 529    | 390                      | 2.9                            | 0.01                                           | 2900                          | [21, 22, 23, 24] |
|                | (1 − 15)             |        |                          |                                 |                                                 |                               |     |
| J1841-045      | 11.77                | 4.1    | 0.4                      | 9.9                            | 0.4                                            |                               | [25, 26] |
| AXP            | (0.1 − 12)           |        |                          |                                 |                                                 |                               |     |
| J170849-4009   | 11                   | 2.25   | 1                        | 6.7                            | 1.5                                            |                               | [27, 28] |
| AXP            | (0.1 − 2.4)          |        |                          |                                 |                                                 |                               |     |
| 0142+614       | 8.69                 | $\sim 0.22$ | 0.1                  | 1.2                            | 0.8                                            |                               | [41, 42, 43] |
| AXP            | (0.1 − 2.4)          |        |                          |                                 |                                                 |                               |     |
| 2259+587       | 6.98                 | 0.06   | 0.2                      | 0.69                           | 3                                              |                               | [29, 30, 31, 32] |
| AXP            | (0.5 − 4)            |        |                          |                                 |                                                 |                               |     |
| 1048.1-5937    | 6.45                 | $\sim 2$ | 0.0063 − 0.3             | 29                             | 0.002 − 0.1                                    |                               | [33, 34, 35, 36] |
| AXP            | (0.1 − 2.4)          |        |                          |                                 |                                                 |                               |     |
| 1806-20        | 7.47                 | 8.3    | 1                        | 78                             | 0.13                                           |                               | [37] |
| SGR            | (0.5 − 10)           |        |                          |                                 |                                                 |                               |     |
| 1900+14        | 5.16                 | 6      | 0.1                      | 320                            | 0.003                                          |                               | [38, 39, 40] |

[1] Haberl et al. 1995; [2] Hanson et al. 1989; [3] Burderi et al. 1998; [4] Levine et al. 1991; [5] Woo et al. 1996; [6] Burderi et al. 2000; [7] Tsunemi et al. 1996; [8] Mereghetti & Stella 1995; [9] Chakrabarty et al. 1997; [10] Angelini et al. 1995; [11] Hutchings et al. 1974; [12] Mavromatakis 1993; [13] Robba et al. 1996; [14] Weisskopf 1984; [15] Li et al. 1978; [16] Vrtilek et al. 1997; [17] Tjemkes et al. 1986; [18] Yokogawa et al. 2000; [19] Bonnet-Bidaut & van der Klis 1981; [20] Kelley et al. 1983; [21] Clark 2000; [22] Clark et al. 1994; [23] Rubin et al. 1997; [24] Robba et al. 1992; [25] Vasisht & Gotthelf 1997; [26] Gotthelf et al. 1999; [27] Sugizaki et al. 1997; [28] Israel et al. 1999a; [29] Baykal & Swank 1996; [30] Fahlman & Gregory 1981; [31] Kaspi et al. 1999; [32] Morini et al. 1988; [33] Corbet & Mihara 1997; [34] Seward, et al. 1986; [35] Mereghetti, 1995; [36] Oosterbroek et al. 1998; [37] Kouveliotou et al. 1998; [38] Kouveliotou et al. 1999; [39] Sonobe et al. 1994; [40] Marsden et al. 1999; [41] Israel et al. 1999b; [42] White et al. 1996; [43] Israel et al. 1994.
Figure 1. $P - \dot{P}$ diagram for PSRs up to 4 kpc. Constant characteristic age lines are from $10^3$ to $10^9$ yrs. Constant magnetic field lines range from $5 \times 10^{10}$ to $5 \times 10^{13}$ gauss. The two curves are from Alpar et. al. 2001