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OLD AND NEW NEUTRON STARS*

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ABSTRACT

The youngest known radiopulsar is the rapidly spinning magnetized neutron star which powers the Crab Nebula, the remnant of the historical supernova explosion of 1054 AD. Similar neutron stars are probably born at least every few hundred years, but are less frequent than Galactic supernova explosions. They are initially sources of extreme relativistic electron and/or positron winds ($\sim 10^{38} s^{-1}$ of 10^{12} eV leptons) which greatly decrease as the neutron stars spin down to become mature pulsars. After several million years these neutron stars are no longer observed as radiopulsars, perhaps because of large magnetic field decay. However, a substantial fraction of the 10^8 old "dead" pulsars in the Galaxy are the most probable source for the isotropically distributed γ-ray bursts detected several times per week at the earth. Some old neutron stars are spun-up by accretion from companions to be resurrected as rapidly spinning low magnetic field radiopulsars.

1. Ancient History[‡‡]

Six thousand years ago a massive star in our Galaxy came to the end of its life in a gigantic explosion. It hurled its debris into the interstellar void at a speed of over 1000 km per second. For a week this expanding blast was more luminous than 10^{10} suns and glowed almost as brightly as our entire Galaxy.

For 5000 years the light from the explosion travelled toward our earth. It arrived here on the 4th of July of 1054 AD from the direction in the night sky known as Taurus (the Bull). It then appeared brighter than all other stars in the heavens, brighter even than Jupiter and Venus and quite visible in the daytime. It surely must have been noticed everywhere on earth where that region of the sky was visible.

The Chinese certainly saw it. The Sung Emperor's court astrologer (or, if you prefer, Chairman of the local Department of Astronomy) reported to him the meaning of this bright new star

> "Prostrating myself before your majesty I hereby report that a guest star has appeared.... If one carefully examines its meaning for the Emperor it is as follows: The fact that the guest star does not trespass into the moon's mansion in Taurus and that it is very bright means that there is a person of great wisdom and virtue in the country. I beg that this notice be given over to the Bureau of Historical Records."
>
> Yang Wei-te

With this interpretation both the announcement of the new super-guest-star and the position of the astrologer were preserved. The Japanese independently observed and recorded this bright new star - a "supernova" - at their medieval

‡‡ Detailed discussions and references are given by Mitton (1978), Clark and Stephenson (1977) and Shklovski (1968).

capital, Kyoto. In all there are at least five independent accounts of it, four Chinese and the one from Japan. Remarkably, there are no European or Russian records. (It has been suggested that the relevant Russian documents were destroyed in the Mongol conquest of Kiev and that European observers in the otherwise Dark Ages did not record a new star which so conflicted with their Aristotelian notions of an unchanging starry heaven. Comets, which often they did record, were thought to be atmospheric rather than heavenly phenomena.)

There is a very intriguing interpretation of certain old American Indian rock drawings which suggests that these may have been records of the supernova observation of 1054 AD. On the morning of July 5, when it was first visible from western North America, the supernova was adjacent to the crescent moon, a figure of the moon rarely found in ancient American Indian rock art. But several "petroglyphs" in Arizona and New Mexico [Fig. 1] have been discovered which may date from the 11th century and which depict a bright-star crescent-moon juxtaposition.

The exploding guest star of 1054 AD was visible during the day for 23 days but after 2 years the supernova could no longer be seen even at night. It disappeared—unseen again until after the invention and development of the telescope in 17th and 18th century Europe. It was first rediscovered in 1731 by an English physician and amateur astronomer, John Bevis, who had an observatory in his house. He produced beautiful copper engraved plates for a planned sky atlas, but his printer went bankrupt as it was being published. Bevis especially noted the exploding supernova remnant [the second "star" in from the top of the Bull's lower horn in Fig. 2] because it appeared as a faint smeared nebulosity rather than as a bright point characteristic of a star. Because the explosion remnant was nebulous instead of pointlike it could be confused with comets which, at that time, were a subject of intense observational interest. The most famous comet of all was Halley's Comet. It returns every 75 years. (This bright comet was depicted in the Bayeux tapestry representation of William the Conqueror's embarkation for England.) In 1682 Halley observed it. He predicted that the comet would return in 1757 when he expected it to pass through the horns of Taurus. The supernova remnant of 1054 AD first reappeared in astronomical reports when it was misidentified as the missing Halley's comet by the French astronomer Messier in 1758. He later gave it the prime listing in his famous catalogue of nebulous astronomical sources. (The true return of Halley's Comet was in fact first seen four months later than Messier's announcement, not by an astronomer with a telescope, but by a French peasant looking heavenward at Christmas time with his naked eye.)

From then on the 1054 supernova remnant became an object frequently observed. The Earl of Rosse observed it through the very large five foot diameter telescope on his estate in the middle of Ireland. His 1844 and 1848 sketches of it are shown in Fig. 3. It looked like a pineapple in 1844 but he named it, after his 1848 drawing of its shape (which suggested the claw of a Crab), the Crab Nebula. And so it is known today. Rosse and most 19th century astronomers assumed that the nebulosity was an artifact of poor resolution and that the Crab Nebula, like so many others, would ultimately be revealed as a dense cluster of many individual stars.

It was only after the application of photography to astronomical viewing that the nature of the Crab Nebula became clear. That nebula is a cloud of gas 6 light years across expanding at 2000 km s^{-1} per second with a bright remnant star near the center of the explosion. The light from that star does not look like the light from familiar stars. Bus this would more easily suggest what the remnant star is not than what it is.

While some scientists looked out at the Universe with their telescopes others explored it only within the confines of their laboratories. In 1932, at the Cavendish Laboratory in Cambridge, England, Chadwick discovered the neutron. The news spread very quickly. On the evening the announcement of that famous discovery reached Copenhagen, Bohr and Landau has a conversation about its implications. Lanuau, on that same evening, proposed that some stars might be composed almost entirely of neutrons.

In Pasadena, a year later, the astronomers Baade and Zwicky proposed that remnant stars of supernova explosions might be such dense stars of neutrons, and they named them "neutron stars." (The suggestion captured the interest of a local reporter. He thought the Caltech astronomers rather mad. But he gave the proposal considerable play in an article in which he also poked fun at them. So, had you lived in Pasadena 50 years ago, you would already have heard of "neutron stars.") Baade and Minkowski (1942) later explicitly suggested the particular star in the projection of the Crab Nebula supernova explosion which was the remnant neutron star.

But how could one verify it? Theorists had calculated estimates for the masses and sizes of such stars but nothing else was known about them. A neutron star should have a mass similar to that of our sun. But most stars have masses in that range and there was no way to weigh the Crab's central star anyway. A neutron star should have a radius of only 10 km, 10^6 times smaller than that of the sun. But, whether it was 10^5smaller or thousands of times larger, the star was so far away that it would still appear as a point to any terrestrial astronomer.

Hoyle, Narlikar and Wheeler (1964), and Woltjer (1964) suggested that in the collapse to a neutron star stellar magnetic fields should get hugely amplified. Pacini (1967) argued that a young neutron star formed in that way could also be rapidly rotating and the spinning magnetic dipole could be the power source of the surrounding nebula (see also Kardashev, 1965). However, there was no way known at that time to test the neutron star hypothesis. That changed 17 years ago with the discovery of pulsars.

The first spinning radiobeaconed neutron star, a "pulsar", was discovered quite accidentally by Bell and Hewish only in 1968, and immediately interpreted as a spinning neutron star by Gold (1968). Among the earliest pulsars found was the remnant central star of the Crab Nebula. That the observed rapidly spinning star, rotating 30 times per second, was a neutron star could have no other reasonable interpretation. The star was rotating so rapidly that, in order not to be pulled apart by the familiar centrifugal forces which accompany fast rotation, it would have to have the predicted huge density and small radius of a neutron star. In addition the input power from the central star needed to account for the emission from the nebula and for the nebula expansion implied that the spinning down central star (Richards and Conally, 1969) had a moment of inertia of about 10^{45} g-cm^2. For a solar mass star this gives a stellar radius of 10 km, just that which theory insists upon for a neutron star (Gold, 1969).

Very shortly after the discovery of the radiopulsar in the center of the Crab Nebula it was found that the visible light of that remnant star was also beamed and sweeping across optical telescopes 30 times per second (Staelin and Reifenstein, 1968). Apparently only relatively rare young rapidly spinning neutron stars beam strongly enough in visible light to be photographed. (The only other known pulsar visible by its flashing light the remnant star in the 10^4 year old supernova in Vela, is also the weakest optical source ever recorded.)

The Crab Nebula's neutron star is also detected as an emitter of x-rays. Figure 4 is a sketch of the Crab Nebula as seen in x-rays. Its central neutron star, although poorly resolved, is now very apparent. As an x-ray source the neutron star is brighter than it is optically, both absolutely and relative to the surrounding expanding nebula. (Had this been our only picture of it, the Crab would probably have been called the Fried Egg Nebula.) As in the optical view of the star the x-ray image flashes on and off 30 times a second as the x-ray beams rotate with the spinning neutron star.

2. Young Pulsars[‡2]

There are other young supernova remnants, most of whose radiation and expansion is powered by a central, rapidly spinning, strongly magnetized neutron star. One that closely resembles the Crab has been discovered recently in the Large Magellanic Cloud. It has a central x-ray and optical pulsar (but the x-ray pulse is broad with a large duty cycle, quite different from the double sharply cusped ones of the Crab pulsar). Some properties of the two nebulae and their central pulsars are compared in Table I.

Helfand (1984) has given arguments that most supernova explosions do not leave the kind of pulsar and nebula now observed in the Crab, characterized by

‡2 For reviews and references see Manchester and Taylor (1977) and Michel (1982).

a young nebula whose visible and x-ray luminosity are powered by super relativistic electron (and/or positron) fluxes generated by a central rapidly spinning magnetized neutron star:

- There are fewer than 5 Crab-like nebulae now observable in our Galaxy suggesting a birthrate of less than 1 per 200 years. The supernova birthrate, on the other hand, is at least several and probably 5 times greater.
- Only 2 of 7 historical supernovae produced Crab-like nebulae. Of the 36 Galactic supernova remnants within 15000 light years searched by the Einstein x-ray observatory satellite, only 6 give indications for central power sources. The other 30 seem to show only the radiation expected from the expanding shock wave created by the initial supernova explosion, but no activity from a remnant neutron star.
- In our neighboring galaxy, the Large Magellanic Cloud, only a tenth of the 25 supernova remnants show evidence for a Crab-like central source.
- The expected thermal x-ray flux from hot newly formed neutron stars has not been detected in most young supernova remnants

The indicated supernova birthrate for rapidly spinning highly magnetized neutron stars such as the Crab or Vela pulsars gives a Galactic population of about 10^8 old neutron stars (10^{-3} of all stars in the Galaxy) formed as they were. If, however, most supernovae either leave behind much more slowly spinning neutron stars ($P \gtrsim 0.3\ s$) whose spin-down energy loss could not power Crab-like nebulae, or neutron stars whose spin-down energy loss could not power Crab-like nebulae, or neutron stars whose magnetic fields grow to Crab-pulsar-like strength only after tens of thousands of years, then the total Galactic population of neutron stars formed in supernova explosions could approach $5 \cdot 10^8$.

It is now fairly clear what a young Crab type remnant neutron star does but very much less clear how it does it.

The Crab pulsar appears to inject a flux of about 10^{38} electrons (e^-) and/or positrons (e^+) into the surrounding nebula with typical lepton energies of order 10^{12} eV. A flux of 10^{38} particles s^{-1} is about 10^4 times greater than would be expected to come from the Crab pulsar unless there is very copious $e^- - e^+$ production in its immediate neighborhood. Kennel (1984) and colleagues have shown that an excellent fit to the spectral and spatial features of the nebula's optical and x-ray radiation is indeed obtained from an unseparated $e^+ - e^-$ wind of this magnitude and the shock that results from it. There is also evidence that similar relativistic winds come from other young pulsars: x-ray synchrotron nebula are observed around pulsars as long as the neutron star spin down power ($-I\Omega\dot{\Omega}$, where I is the theoretical neutron star moment of inertia, Ω its spin rate, and $\dot{\Omega}$ its deceleration) exceeds about 10^{35} erg s^{-1} (Helfand, 1982; Cheng and Helfend, 1983). (Typical mature pulsars have $I\Omega\dot{\Omega} \sim 10^{32} erg\, s^{-1}$).

Important clues to the mechanisms by which the Crab pulsar generates the particle input to its superrelativistic wind come from observations of its rotating beams of radiation. These carry away less than 10^{-2} of its spin-down energy loss. They consist of a pair of beams, probably fan shaped, 140° apart in phase, with an observed spectrum containing microwave, IR, optical, soft x-ray, MeV, GeV, and probably 10^{12} eV photons. Coincidences in timing and in beam phase separation seem to imply that all of these photons, with a spectrum extending over 18 orders of magnitude in frequency, come from the same physical location around the pulsar. There are many models (really semiqualitative suggestions) but certainly no consensus on how the pulsar accomplishes this. Part of the theoretical problem is the richness of relativistic quantum as well as classical electrodynamic and plasma phenomena that may be relevant. Even at 10^2 stellar radio from the Crab pulsar (near the "light cylinder" radius, $c\Omega^{-1}$, where corotating plasma around the neutron star must spin at the speed of light) the steady power flux away from the star reaches 10^{15} watts cm^{-2}—equivalent to that of the total electric power generated on the earth flowing through a hair-thin wire or an entire nuclear war every second in one square meter.

There is, so far, no terrestrial laboratory analogue for a young, spinning, magnetized, neutron star: A spinning object will generally break apart when parts of it move with respect to other parts at speeds faster than the sound velocity (v_s) within the object. For strong terrestrial matter $v_s \sim 10^5\, cm\, s^{-1}$. The parameters, electric fields, and potential drops from a 60 Hz electric power generator are compared in Table 2 to those outside of a Crab-like neutron star spinning in a vacuum.

In the presence of such huge electric fields the region outside of the spinning neutron star will become almost completely filled out to the light cylinder with a corotating plasma (the "magnetosphere") flowing to short out components of $\underset{\sim}{E}$ parallel to $\underset{\sim}{B}$. Some of this plasma can be pulled from the stellar surface (or, in one model, from a Keplerian disk around the star). An $e^- e^+$ plasma will be created whenever $\underset{\sim}{E}$ and ΔV are sufficiently large to support the production of γ-rays of high enough energy to materialize as pairs. Such γ-rays can created pairs in three ways:

1. Conversion on strong magnetic fields (Sturrock, 1970).

$$\gamma + \underset{\sim}{B} \rightarrow e^+ + e^- + \underset{\sim}{B}$$

This is important for γ-rays in the MeV-GeV range as they begin to cross the strong magnetic field ($\sim 10^{12}G$) near the neutron star. (For special problems with stronger fields see Shabach and Usar, 1982.)

2. Conversion by collisions with x-rays (γ_x).

$$\gamma + \gamma_x \rightarrow e^- + e^+$$

for multi-GeV γ-rays.

3. Conversion by collisions with soft (optical or IR) photons (γ_ν).

$$\gamma + \gamma_\nu \rightarrow e^- + e^+$$

for 10^{12} eV γ-rays.

The needed energetic γ-rays can be radiated (often by the $e^- - e^+$ particles they themselves create) by three mechanisms:

a) Curvature radiation from accelerated e^- or e^+ constrained to move along curved magnetic field lines.

b) Inverse Compton scattering of extreme relativistic e^- or e^+ on soft photon fluxes which give large local photon number densities.

c) Synchrotron radiation from extreme relativistic electrons spiralling along magnetic field lines.

It has been recognized that, because of plasma flow away from the star, large electric fields and potential drops may build up along certain magnetic field lines both near the light cylinder (outer magnetosphere) and also much closer to the stellar surface (inner magnetosphere) until pair creation (or Keplerian disk sources) supply net local charge deficiencies.

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A necessary condition for copious outer magnetosphere $e^- - e^+$ production (by processes 2) and 3)) is that electric fields there, in the absence of pair production, are able to accelerate electrons to enough energy to create the needed energetic photons despite radiation reaction or soft photon inverse Compton drag. An approximate cut-off for copious outer magnetosphere pair production occurs when even the complete absence of charged plasma on those magnetic field lines which penetrate the light cylinder (it is on these "open" field lines that outflowing plasma must be continually replenished) does not give a potential drop along $\underset{\sim}{B}$ exceeding about 10^{14} volts (Cheng et al., 1984). For a surface magnetic field $B(\equiv 10^{12}B_{12}G)$ this limit corresponds to

$$B_{12}/P^2 \sim 20 \ . \qquad (1)$$

Pair production in the much stronger magnetic field near the neutron star will on longer be sustained if ΔV along $\underset{\sim}{B}$ falls below around 10^{12} volts (Sturrock, 1970; Ruderman and Sutherland, 1975), corresponding to the limit

$$B_{12}/P^2 \sim 0.2 \ . \qquad (2)$$

These limits are simply related to spin-down energy loss rates in conventional pulsar spin-down models by

$$I\,\Omega\dot{\Omega} = \dot{E} \sim R^6 c^{-3} B^2 \Omega^4 \sim \left(\frac{B_{12}}{P^2}\right)^2 10^{32}\, erg\, s^{-1} \ . \qquad (3)$$

Copious outer magnetosphere pair production would then not be expected if $\dot{E} < 4 \cdot 10^{34}\, erg\, s^{-1}$ in agreement with the observation mentioned above, that pulsars with $\dot{E} > 10^{35}\, erg\, s^{-1}$ have synchrotron x-ray halos attributed to a strong outflow from them of extreme relativistic e^- and/or e^+. When $L < 4{\cdot}10^{30}\ erg\,s^{-1}$, even inner magnetosphere pair production is expected to be extinguished. For most theoretical models this would also imply that the spinning neutron stars would no longer be radiopulsars. There is, at present, no consensus that the extraordinarily rich and broad electromagnetic radiation spectra from the young Vela and Crab pulsars is associated with outer magnetosphere pair generation, to say nothing of the precise source location or the specific radiation mechanisms.

As pulsars spin down their radiation spectra become much more limited as indicated on Table 3.

The "measured" surface B (from Eq. (3)) is shown for a local population of pulsars in Fig. 5. Because of selection effects and uncertain beaming corrections it is not possible to read with confidence evolutionary tendencies or pulsar birthrates from these data. (Many, perhaps most, may be born spinning much more slowly than the Crab pulsar.) A common interpretation of the distribution of $B \propto (P\dot{P})^{1/2}$ vs. P is that the surface magnetic fields of typical neutron stars decay to a much smaller value on a time scale of several $\cdot 10^6$ years. This would quickly carry them across the $\Delta V \sim 10^{12}$ volts threshold of Eq. (2), after which they would no longer be observable as radiopulsars. Corroborative support comes from the observation that most radiopulsars are moving rapidly ($\sim 180\ km\,s^{-1}$) away from the Galactic plane where they were born, but are still sufficiently close to the plane that their true age since birth must be less than 10^7 years. There is no consensus on how (or even when) pulsar magnetic fields are formed or on why (or even whether) they decay (Flowers and Ruderman, 1977; Blandford et al., 1983). However estimates for the lifetime of currents in the crystalline crust of a neutron star do suggest that magnetic fields which owe their existence or stability to such currents may decay after several $\cdot 10^6$ years. Other field relaxation processes have also been suggested (Chanmugan, 1984). Thus observations seem to indicate and current theory is at least comfortable with a population in our Galaxy of $(1-5)\cdot 10^8$ old $(10^7 - 10^{10}$ years) low magnetic field neutron stars.

3. Old Neutron Stars

Several developments in the past few years have served to emphasize that many of these old neutron stars are not only not inert but at times are even much livelier than when they were young.

It has been known since the early days of x-ray astronomy that there exists a population of neutron stars which accrete matter from nearby normal companion stars. These are observed by the thermal KeV x-rays from accretion or from explosive bursts from the sudden fusion of infalling hydrogen and helium rich matter. There are probably between 35 and 300 such x-ray binaries in the Galaxy. For most there are indications that the binary is very old and also that the neutron star in it has a much lower magnetic field than that of most radiopulsars (too small to affect the infall of matter onto the neutron star or to modulate thermal x-rays from its rotating surface).

Recently two new classes of apparently old neutron stars have become foci of interest; γ-ray bursters and resurrected pulsars.

a) *Resurrection of Pulsars*[13]

Figure 5 includes four radiopulsars which are members of binaries. Two of them,

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13 For reviews and references see Reynolds (1984)

PSR 1953+29 and 1913+16 (the Hulse-Taylor neutron star binary), are not in the parameter space defined by other pulsars and one, PSR 0655+64 lies at its boundary. All of these pulsars have the anomalously low surface magnetic fields (as defined by Eq. (3)) seemingly characteristic of "old" neutron stars, but the very short periods otherwise found only in young pulsars. They are, indeed, all probably old neutron stars. However, when their companions where younger, there was a transfer of stellar matter from the companions to Keplerian accretion disks around the neutron stars. This surrounding disk could have spun-up a neutron star until the neutron star spin velocity and that of its corotating magnetosphere matched that of the inner edge of the accretion disk (Rhadhakrishnan and Srinivasan, 1981; Damashek et al., 1982). While magnetospheric corotation for isolated magnetized neutron stars can extend to the light cylinder, for accreting ones the magnetosphere terminates at the inner edge of the accretion disk where disk inflow pressure balances the neutron star's magnetic pressure. Thus the inner disk radius and the ultimate spin-up velocity of the neutron star depend upon the accretion rate and the neutron star's magnetic field (Ghosh and Lamb, 1974; Davidson and Ostriker, 1973; and van den Heuvel, 1977).

While accretion continued such binaries would have been observable as x-ray sources. Only after accretion stopped would they be expected to become radiopulsars if (B, P) for the spun-up neutron star again lies above the $\Delta V \sim 10^{12}$ volt (pair-production) turn off line. The so resurrected pulsar period

$$P \sim B_8^{6/7} \left(\dot{M}/10^{-8} M_\odot \, yr^{-1}\right)^{-3/7} \text{ sec.} \qquad (4)$$

where $\dot{M}$ is the mass accretion rate during spin up. The maximum value for $\dot{M} \sim 10^{-8} M_\odot$ year, the "Eddington limit" at which gravitational pull is balanced by x-ray radiation pressure, a value approached in many observed accreting x-ray sources. This is used for the otherwise parameter free theoretical spun-up radiopulsar birth line in the (B, P) space of Fig. 5. The three binary pulsars with measured $\dot{P}$ lie near this birth line, and the deviations are toward that side of the zero-age birth line where reduced $\dot{M}$ and/or post-rebirth spin-down would put them. A fourth binary pulsar, PSR 1953+29 (Boriakoff, 1984), has only a measured upper bound for $\dot{P}$ and B. The most interesting of the very short period pulsars is PSR 1937-214, the first millisecond pulsar (Backer et al., 1982). It too lies on the binary accretion spin-up birthline, which encourages the hypothesis that it was also spun-up by accretion from a companion (Alpar et al.)[‡4] (A total accreted mass of about 0.1 $M_{\odot}$ would be needed.) Unlike the other putative spun-up pulsars PSR 1937-214 does not have a companion. Three kinds of explanations[‡5] have had numbers of proselytizers:

1. Parthenogenesis: There never was another star involved in the birth of the millisecond pulsar; it was formed from the collapse of a single low magnetic field high-spin stellar core.

2. Transfiguration: The Hulse-Taylor binary pulsar consists of two neutron stars in an orbit that is contracting because of gravitational radiation. In about $4 \cdot 10^8$ years they will coalesce and may leave behind a single hot, high spin angular momentum, low magnetic field neutron star (or a black hole).

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‡4 Like PSR 1953+29 it also lies almost exactly in the Galactic plane suggesting that both may have been form, not in canonical supernova explosions, but by accretion onto a White Dwarf until the Dwarf mass exceeded the Chandrasekhar limit. The resulting implosion and mass loss may then have been sufficiently gentle to keep the intact binary from acquiring a large recoil velocity.

‡5 For a review see for example van den Heuvel (1984) and Ruderman and Shaham (1983).

3. Resurrection and Sacrifice: The neutron star is spun-up into the radiopulsar regime by an accretion disk which is well fed by mass loss from a companion. The companion is then tidally disrupted by the gravitational field of the neutron star.

When the companion is degenerate (or fully convective) its radius (R_2) generally increases as its mass (M_2) decreases (cf. Fig. 6). Avoiding catastrophic tidal disruption by a heavier neutron star is then not always easy to accomplish if the companion is too close. Tidal disruption seems always to occur to a companion White Dwarf with $M_2 > 0.7\,M_\odot$ around a cold $1.4\ M_\odot$ neutron star whenever the binary separation is close enough to allow *any* mass to be pulled from the companion to the neutron star (van den Heuvel, 1984). It may also happen to a very light degenerate (H_e) companion when its mass loss to the accreting neutron star brings $M_2 < 4 \cdot 10^{-3} M_\odot$, especially if the tidal disruption time of the secondary (several minutes) is less than the expansion time of the neutron star's accretion disk as matter is rapidly fed into it (Ruderman and Shaham, 1983). Catastrophic tidal instability of a light degenerate companion may also be triggered when the binary is perturbed by a passing star (Webbink et al, 1984). Even if only gravitational radiation is removing angular momentum from the binary this critical stage will be reached in less than the age of the Galaxy.

One suggested scenario (Ruderman and Shaham, 1984) for the spin-up of the now isolated millisecond pulsar is that angular momentum was transferred to an old low magnetic field neutron star by accretion from a low mass companion as is presently observed in so-called "Galactic bulge x-ray binaries." The companion may have begun its life as a light main sequence star burning hydrogen in a central core. When its mass decreased to of order $10^{-1}\,M_\odot$ its core burning would cease, leaving a cooling Dwarf star with a very small largely helium core, much denser than the rest of the star. The heavy helium core would not be convectively mixed as the companion cooled to degeneracy. The R_2 versus M_2 behavior of such a star is sketched in Fig. 6. As mass is lost to the neutron star from the outer hydrogen layers of the inhomogeneous degenerate Dwarf, R_2 first grows, then contracts as the He core is approached, and then expands again after the core is revealed. For stable mass transfer the binary separation $\hat{a} \sim R_2(M_{NS}/M_2)^{1/3}$ has a similar behavior. If the He core boundary is idealized as a zero thickness shell, dR_2/dM_2 becomes infinite as the shell is reached. This would mean that $\hat{a}$ shrinks at that stage without any mass transfer: there would then be no accretion disk around the neutron star. The "sudden" resumption of R_2 expansion when the He core is reached, in the absence of an accretion disk to transfer angular momentum to the companion and rapidly expand $\hat{a}$, would then certainly tidally disrupt the so-modelled companion. Another scenario for removing a companion star (van den Heuvel, 1984) exploits the tidal instability of a heavy 0.7 $M_\odot$ Dwarf companion when it fills its Roche lobe. In either case tidal disruption is invoked after the companion gets "too close for comfort."[♯6]

b) *γ-ray bursts*[♯7]

Cosmic bursts of soft γ-rays (typically $10^{-5}\,erg\,cm^{-2}$ of 10 keV-10 MeV x-rays over several seconds) are detected at the earth at a rate of about 1/64 hours. They are isotropically distributed and have a number versus intensity distribution which now appears consistent with a homogeneous distribution. Thus the sources

♯6 In this confusion of the biblical story, in the beginning a companion transferred original spin to the neutron star. By this passover it resurrected the dead neutron star into a live radiopulsar, sacrificed itself, and became wholely a ghost.

♯7 For reviews and references, see Liang and Petrosian (1985), Hurley (1983), Woosley (1984a,b), Lamb (1984), Strong et al. (1975) and Ruderman (1975).

may be so close that the disk structure of our Galaxy is irrelevant, or part of a halo population, or extragalactic. The short time scale for intensity variations—typically 10^2 ms but less that 0.3 ms in one case—argues that the spatial size of the radiating region is far less than canonical stellar radii. Recent observations of substantial (non-thermal) 10-40 MeV components in some bursts is rather compelling evidence for the local source hypothesis. An extra-galactic source would need an intrinsic x-ray luminosity over 10^4 times larger than a local one to give the same observed bursts. However the x-ray photon density near a compact extra-galactic source would then be so large that the short mean free path for $e^- - e^+$ production by 10-40 MeV γ-rays would not permit those γ-rays to escape from the source.

Therefore modellers are comfortable with the existence of 10-40 MeV components to γ-ray bursts from compact sources only when the characteristic distance to them is not greater than about several $\cdot 10^2$ light years. A further indication of the source population comes from observational bounds on the repetition rate for bursts from any one source. Observations suggest that the repetition rate does not exceed about 1/year, but that some, perhaps all, burst sources do repeat. [At least one source (an anomalous one called the "March 5 event") and possibly a second (the "40 longitude source") have been observed to repeat in γ-rays. Other evidence for repetition comes from historical records of optical transients presumed coincident with γ-ray bursts (e.g. Schaefer, 1981).] The maximum average repetition rate gives a needed population of $\gamma-$ ray burst sources within, say, 300 light years of about 10^7, comparable to the expected number of all "dead" old neutron stars in that volume. The needed compactness of the source size and the relatively large (compared to ordinary stellar events) burst energy

($\sim 10^{37}$ *ergs*) are additional circumstantial evidence pointing to part of the local old neutron star population as the source of γ-ray bursts. Although isolated old neutron stars may occasionally have structural "glitches" these would not be sufficiently frequent, large, or release energy rapidly enough to be the γ-ray burst sources. Speculation and modelling have been directed mainly toward old neutron stars in binaries, accreting so slowly from underluminous companions that neithe are yet detectable as steady sources. Burst energy would come either from accretion disk instabilities or from subsurface nuclear fusion explosions.

The release of 10^{38} ergs of γ-rays would require an accreted mass of $10^{18}\,g$ if all the energy came from gravitational binding (accretion disk instability), $10^{19}\,g$ if hydrogen fusion was the source, and $10^{20}\,g$ for explosive helium burning. For a nominal 3 year burst repetition interval the explosive fusion models would them imply thermal x-ray sources during the accretion in the range $10^{31} - 10^{32}\,erg\,s^{-1}$, low enough so that they might escape detection as steady x-ray sources. If, as expected, the accretion is through the intermediary of a Keplerian accretion disk around the neutron star the neutron star's spin will ultimately approach the period P given by Eq. (4). Since $(10^{18} - 10^{20})g\ (3\,yr)^{-1} \sim (10^{-16} - 10^{-14})\,M_{\odot}\,yr^{-1}$, $P \sim 3^{\pm 1}\ B_8^{6/7}$ sec. Thus the old neutron stars which are the most attractive candidates for γ-ray burst sources should be rotating with a period that depends upon their magnetic fields in a manner similar to that for resurrected pulsars. There are some indications of periodicity in γ-ray burst observations. The 1979 "March 5 event" certainty has an 8 sec periodicity (e.g. Barat et al., 1979) but it is a very atypical repeating burstor. Wood et al. (1981) discuss a 4.2 sec period for the 1977 October 29 burst. Barat et al. (1984) consider the plausibility of a 5.7 sec period in the 1979 January 13 burst data. Evans et al. (1980) discuss others in the several second range. If these periods are those of the accretion disk spin stabilized neutron star which is presumed to be the burst source, they would indicate $B \sim 10^9\,G$. This is quite reasonable for an a old neutron star since it is similar to that of those which, with enormously stronger accretion rates, seem to have been spun up to be millisecond pulsars. Moreover such a weak magnetic field would easily allow 20-40 MeV γ-rays to escape from the neutron star surface without pair creation, much more difficult to accomplish if B had the $10^{12}\,G$ which seems typical for younger neutron stars (at least those which are radiopulsars). However, if the magnetic field is so weak it may be harder to see how the rotation of the star would so strongly control the window for observing high energy radiation ($\hbar eB/mc \sim 10\,eV$ for $B \sim 10^9\,G$). Further Woolsey and others (1984b) (Petrosian and Liang, 1985) have martialled arguments that the qualitative features of γ-ray bursts from thermonuclear explosions are very difficult to interpret unless $B \sim 10^{12}\,G$. Finally, a notch in the (time averaged) burst photon energy spectrum has often been interpreted as evidence for cyclotron absorption (or emission) with $B \sim$ several $\cdot\, 10^{12}$ Gauss. Thus there are also indications that this family of old neutron stars has strong magnetic fields. Much remains to be understood.

It is a pleasure to thank Professor Sidney Drell and the Theoretical Group at SLAC for their kind hospitality and the Aspen Physics Center where this work was begun.

APPENDIX

The following are a list of questions put to the August 13-31 Aspen Center for Physics workshop "New Directions in Pulsar Physics" by the workshop organizers.[§8] Generally a consensus on answers was not reached so that it is a somewhat idiosyncratic outline of neutron star research remaining to be done.

1. *Magnetic Fields*
   Why do radiopulsars have similar magnetic fields at similar "ages"?
   Why do millisecond pulsars have such weak fields? Why do Galactic bulge x-ray source neutron stars have such weak fields?
   Is B primordial or generated during the life of the neutron star or both?
   Do core magnetic fields decay?

2. *Radioemission from Pulsar Magnetospheres*
   Are e^+e^- pairs necessary?
   Does pulsar turn-off (on) coincide with pair production turnoff (on)?
   Where are pairs made?
   Why doesn't back-flow heat pulsars so that they are observed as x-ray sources?
   Do all radio-pulsar magnetospheres also emit γ-ray beams?
   Why is only the Crab a strong optical pulsar?
   Why are the Vela and Crab pulsars such strong γ-ray sources?
   What is the origin of the pulsar radioemission?
   How is radiopulse fine structure related to background plasma instabilities and/or large amplitude wave instability?
   What is the origin of the occasional giant radiopulses from the Crab pulsar?

3. *Beyond the Light Cylinder*
   What comes out?
   How anisotropic is the wind?
   Are ions emitted? e^+/e^- pairs?
   Is the plasma charge separated or an MHD wind?
   How large is acceleration beyond the light cylinder?
   Can isolated pulsars produce relativistic jets?
   When are synchrotron nebulae formed?

§8 C. Kennel, D. Pines, M. Ruderman, and J. Shaham

4. *Basic Pulsar Plasma Physics*

How do super-relativistic shocks accelerate particles?

What is the plasma physics of the strong magnetic field strong radiative capture regime?

What is the appropriate description of large amplitude waves and particle acceleration?

5. *Birth and Dealth of Pulsars*

Are supernovae abundant enough to give the needed birth rate?

Can pulsars be formed "quietly"?

Are pulsar corpses still spinning down?

How might they be detected?

Do dipoles align with the spin axis near pulsar turn-off?

How much of torque decay is from field decay versus how much from alignment?

6. *Neutron Star Structure and Mass*

What are the current handles on stellar radius, internal structure, and mass?

Is there evidence for a range of neutron star masses?

Are masses and red shifts known well enough to pin down the neutron star equation of state?

7. *Neutron Star Cooling*

What role is played by magnetic fields?

What is the current status of the observational constraints?

Is it physically reasonable to argue that the Crab pulsar has an internal temperature some 25 times that of the Vela pulsar?

Should there be a spin-modulated thermal x-ray pulse from Vela?

8. *Timing Noise, Glitches, and Post-Glitch Behavior*

Does pulsar timing noise scale with $\dot{P}$? with $\dot{P}/P$?

What kind of noise has thus far been observed?

What are the likely physical origins of timing noise?

Why are the Vela pulsar glitches so different from those observed for the Crab pulsar?

Can one fit all observed post-glitch behavior of all pulsars with the pinned vorticity model?

9. *Millisecond Pulsars*

Was the millisecond pulsar 1937+214 formed in an isolated event or in a binary?
If a binary, what happened to the companion?
Why are the two most rapidly spinning pulsars almost exactly in the Galactic plane?
How old is the millisecond pulsar?
Does it have a synchrotron nebula?

10. *γ-ray Bursts*

Are neutron stars the sources of γ-ray bursts?
Are the stars isolated or in binaries?
Are bursts a results of accretion instabilities or pyconuclear explosions?
Are the stellar magnetic fields large ($B \gtrsim 10^{12}G$) or small ($B \lesssim 10^{10}G$)?

11. *Peculiar Objects Which May be Neutron Stars*

What are:

(a) Cyg x-3

(b) Geminga

(c) March 5 event

(d) SS 433

(e) Nemesis ??

12. *Superenergetic γ-rays from Neutron Stars*

Is Cyg x-3 an accreting neutron star and a source of 10^{15} eV γ-rays? How are the γ-rays produced so efficiently?
What is the source of claimed 10^{12} γ-rays from the Crab and Vela pulsars?
What other pulsars should be sources of pulsed γ-rays of energy $\gtrsim 10^{12}\,eV$?

13. *Environmental Impacts*

Do pulsars depress the stock market, increase crop yields, and play beautiful music?

TABLE 1

	LMC 0540–69	Crab
Nebula		
diameter	2 psc	2 psc
expansion velocity	1600 $km\,s^{-1}$	2000 $km\,s^{-1}$
mass	$\gg 1 M_\odot$	$\sim 10 M_\odot$
x-ray luminosity L_x	$9 \cdot 10^{36}\ erg\,s^{-1}$	$2 \cdot 10^{37}\ erg\,s^{-1}$
Pulsar		
period (P)	50 ms	33 ms
spin down rate ($\dot{P}$)	$480 \cdot 10^{-15}\ ss^{-1}$	$430 \cdot 10^{-15}\ ss^{-1}$
spin down energy loss rate $\dot{E}$	$2 \cdot 10^{38}\ erg\,s^{-1}$	$5 \cdot 10^{38}\ erg\,s^{-1}$
surface magnetic field B	$4 \cdot 10^{12}\ G$	$3 \cdot 10^{12}\ G$
"age" $t \equiv P/\dot{P}$	1660 yrs	1200 yrs
$L_x/\dot{E}$	.05	.05

Properties of the Crab and LMC 0540-69 Pulsars (Helfand, 1984). The last four lines are inferred from others above. $\dot{E} = (2\pi)^2 I\dot{P}P^{-3}$ where I is the theoretically estimated moment of nertia. B is estimated from the spin-down torque needed to achieve $\dot{E}$ according to Eq. (3).

TABLE 2

	Crab neutron star in vacuum	Electric utility power generator
F (sec)	$3 \cdot 10^{-2}$	$2 \cdot 10^{-2}$
$R (cm)$	10^{6}	10^{2}
$\underset{\sim}{B}$ $(Gauss)$	10^{12}	10^{4}
$\underset{\sim}{E}$ $(Volts\ cm^{-1})$	10^{12}	10
ΔV $(Volts)$	10^{16}	10^{3}

Comparison of properties of a terrestrial rotating electric power generator with those of the rapidly rotating neutron star which powers the Crab Nebula. The pulsar electric field and potential drop are estimated for an empty magnetosphere.

TABLE 3

pulsar	age (yrs)	number in Galaxy	strong radiation beams
Crab	930	$\lesssim 10$	RF, optical, x-ray, γ-ray
Vela	10^4	$\lesssim 10^2$	RF, γ-ray
typical pulsar	10^6	10^4	RF
"dead" pulsar	10^{10}	10^8	

Age, population, and strong radiation beams from spinning neutron stars.

FIGURE CAPTIONS

1. Two ancient southwest United States petroglyphs which may represent the sudden appearance of the supernova of July 5, 1054 near the crescent moon (Minton, 1978; Shklovski, 1968).

2. The engraving for John Bevis' Sky Atlas which shows the neb · · supernova remnant as the second star from the tip of the lower horn.

3. Lord Rosse's sketches of the Crab Nebula. The left one was drawn in 1848, the right in 1944.

4. A representation of the Crab Nebula and its neutron star as observed in x-rays.

5. The surface (dipole) magnetic fields of pulsars (B) from Eq. (3) versus their periods (P) adapted from van den Heuvel (1984) and Rhadhakrishnan and Srinivasan (1981). An equivalent representation is in Alpar et al. (1982). The four binary pulsars are indicated by circled dots; the isolated milliseconed pulsar is shown with a square. The binary 1953+29 has only an upper bound for $\dot{P}$ and B (Boriakoff, 1984). Spin down ages $P\dot{P}^{-1}$ in (BP) space are solid diagonals labelled 10^3, 10^6, and $6 \cdot 10^6$ years. The dashed trajectory with $B_0 = 3 \cdot 10^{12} G$ indicates the model evolution for P and $\dot{P}$ related by Eq. (3) when the neutron star magnetic field decays exponentially on a scale $3 \cdot 10^6$ years. The dash-dot line is the theoretical radiopulsar turnoff of Eq. (2). The dashed diagonal is the theoretical birth curve for pulsars spun up by Eddington limit accretion from a companion according to Eq. (4).

6. Radius (R) versus mass (M) for cold degenerate stars. The upper solid curve is for pure hydrogen. The lower for pure helium and the $x = 0.25$ for a cosmological mixture of 25% He and 75% H by mass. Solid state corrections of Zapolsky and Salpeter (1969) are included. The dashed trajectory indicates the evolution of a mainly H white drawf with a $10^{-2} M_\odot$ He core. The vertical bars indicated where the star will be after $2 \cdot 10^{10}$ years when they have 1 $M_\odot$ neutron star companions to which they are continually brought closer (always filling their Roche lobes) by the loss of angular momentum to gravitional radiation.

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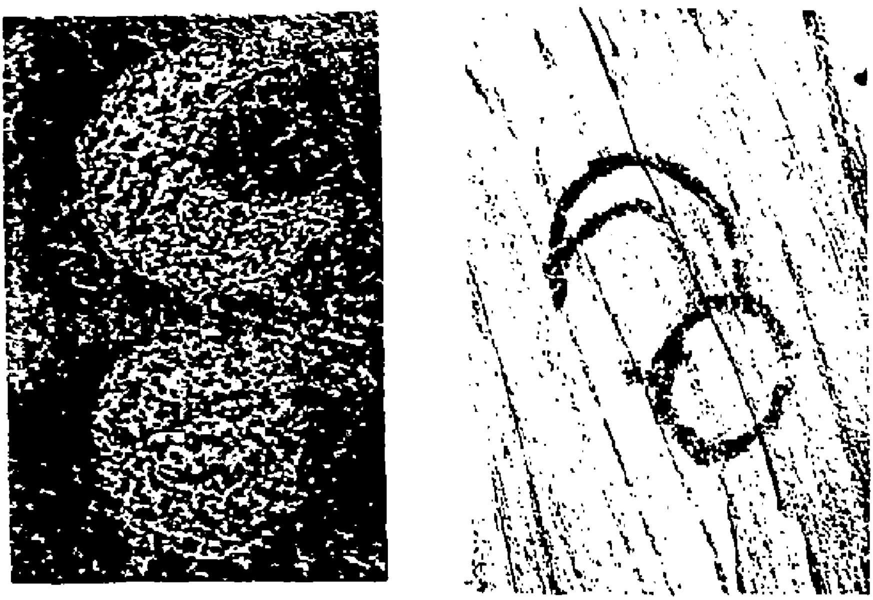

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Fig. 1

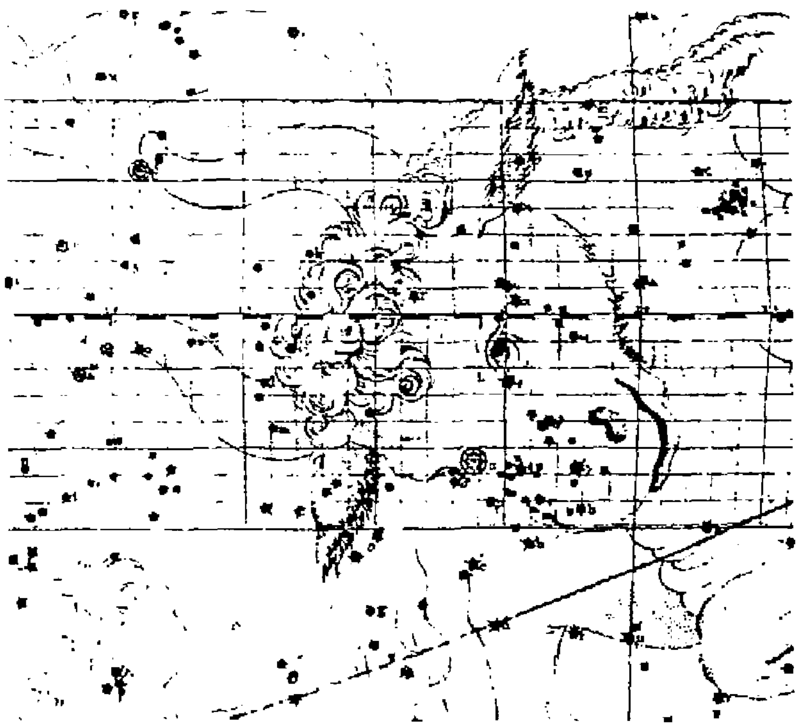

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Fig. 2

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Fig. 3

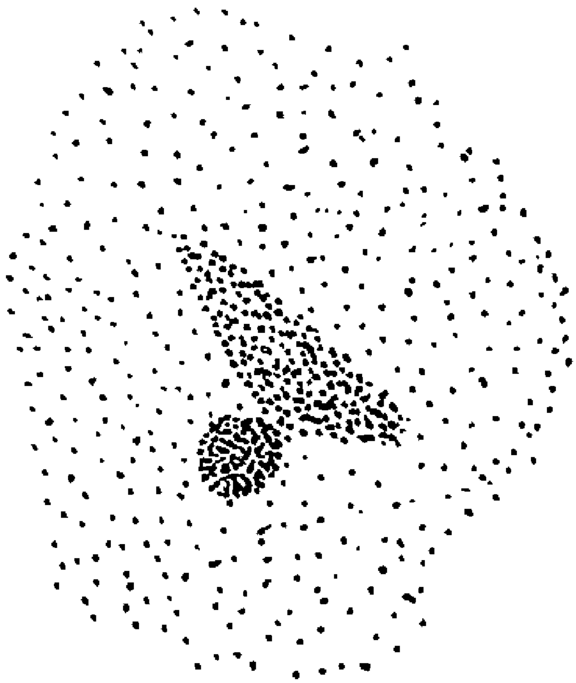

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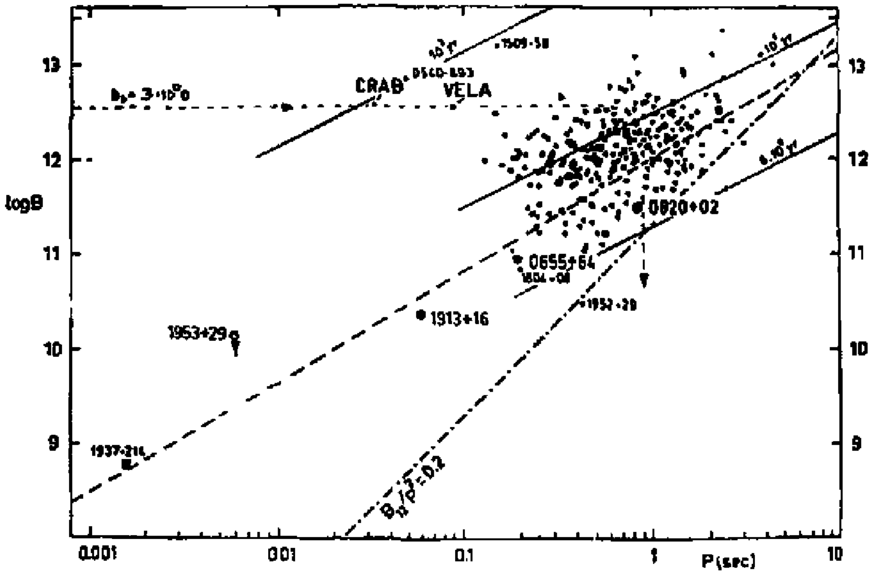
Fig. 4



13
12
11
10
9
logB
0.001
0.01
0.1
1
P(sec)
10
CRAB
VELA
0655+64
0820+02
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1953+29

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Fig. 5

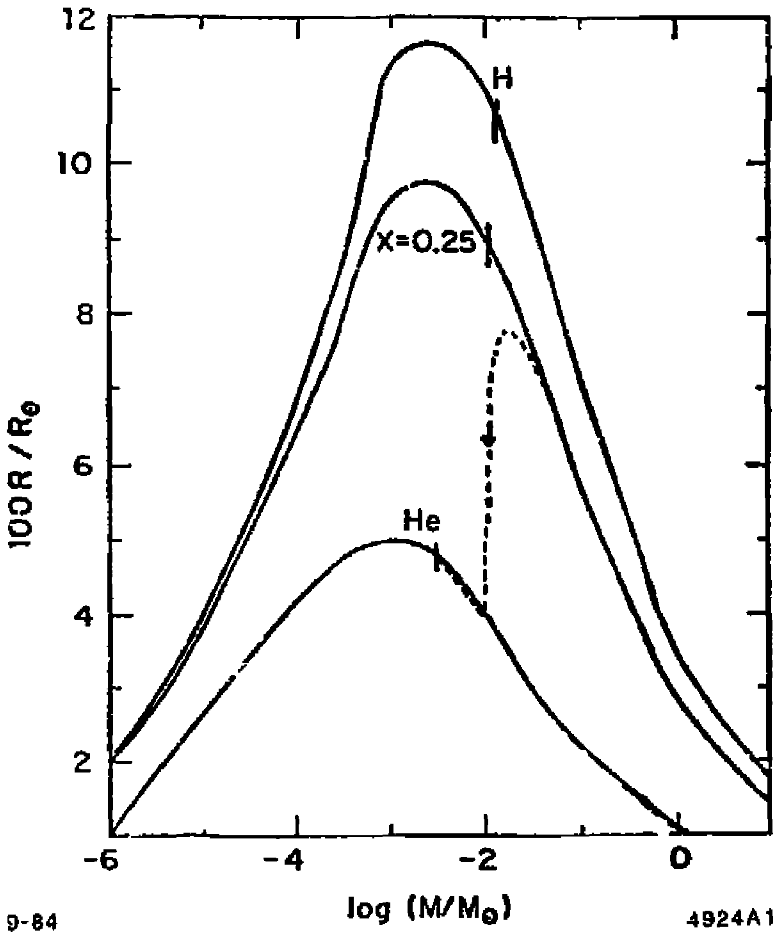

Fig. 6