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RADIATION DOSIMETRY OF BINARY PULSARS

DAVID EICHLER
Department of Physics, Ben-Gurion University, Beer-Sheva, Israel; eichler@bguvms.bgu.ac.il
AND
BIMAN B. NATH
Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune-411007, India; biman@iucaa.ernet.in
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ABSTRACT

Companion stars exposed to high-energy radiation from a primary neutron star or accreting black hole can experience significant spallation of their heavy elements; in this case, their atmospheres would be extremely rich in Li, Be, and especially B. In this paper, we note that the detection or nondetection of these elements, and their relative abundances if detected, can provide a diagnostic of the high-energy output of the primary and, possibly, the shock acceleration of particles at the companion's bow shock in a pulsar wind.

Subject headings: binaries: close — nuclear reactions, nucleosynthesis, abundances — pulsars: general

1. INTRODUCTION

Pulsar emission theory is by now an established, if unresolved, topic. Radio pulsations are believed to imply counter-streaming pairs, which are produced via the curvature radiation of very high energy gamma rays. Below the "death line," it is believed, the primary radiation is mainly curvature radiation that fails to develop a next generation of pairs. Even while pulsing, a pulsar can easily put out $\sim 10^{-3}$ of its spin-down energy as pulsed gamma rays (Usov 1983) since (1) pair production shorts out the field to the point that the pairs are accelerated only enough to marginally produce additional pairs and (2) charged particles that are accelerated outward will eventually reach a site where emitted photons can escape without further pair production. A reasonable estimate for curvature radiation is probably the product of the Goldreich-Julian current and the polar voltage drop, which suggests the fraction of total spin-down power radiated as curvature gamma rays can be of order 10^{-3} or more for millisecond pulsars. Luminous, nearby pulsars such as the Crab are observed to yield pulsed gamma rays at a total power consistent with theoretical expectations based on this estimate. Recent EGRET limits are also consistent with these expectations (Fierro et al. 1995). However, additional gamma radiation may be generated by pairs' striking and cascading in the atmospheres of companions to pulsars. In addition, the pair luminosity itself may be enhanced by shock acceleration of pulsar wind particles at the bow shock of its companion (Arons & Tavani 1994; Grove et al. 1995).

In this paper, we suggest that the output in high-energy ($E > 20$ MeV) quanta from pulsars with close binary companions can be diagnosed via the production of light elements in the companion's atmosphere by photospallation. The idea of using light elements as a dosimetric diagnostic of pulsars is not new, having been discussed in the context of very young pulsars irradiating early supernova remnants (Eichler & Letaw 1987). More recently, Li was reported to be present in roughly cosmic abundances in V404 Cyg, contrary to expectations that most of it would have been destroyed, and we have considered that the Li was replenished by photospallation caused by irradiation from the compact (primary) companion. This explanation invokes some numerical coincidence, though; alternative explanations for the Li abundance in V404 Cyg–like systems are briefly mentioned in § 3.

The question of whether "black widow"–type evaporation scenarios occur for accreting neutron stars and pulsars is still an open one. It has been suggested that heat-induced evaporation can be important in companions to both accreting neutron stars and pulsars (Eichler & Ko 1988; Ruderman et al. 1989b; Ruderman, Shaham, & Tavani 1989a), though the efficiency of mass loss and extent of ablation have been questioned on both observational and theoretical grounds (Levinson & Eichler 1991; Eichler 1991; Gedalin & Eichler 1993). This matter is particularly in question for low-luminosity pulsars, where some mechanism must be invoked for conversion of the spin-down power to a form of energy suitable for mass evaporation. In this case, some scenarios assume that the pulsar's spin-down power is somehow converted to soft gamma rays with high efficiency (Kluzniak et al. 1988; Phinney et al. 1988). Several eclipsing pulsars have been discovered at this time (Fruchter et al. 1988; Lyne et al. 1990; Johnston et al. 1992), and the eclipse is suggestive of some mass-loss mechanism, though not necessarily implicative of significant ablation. In the PSR 1957+20 system, for example, viable eclipse mechanisms typically require a plasma frequency at the eclipse site of ~ 0.1 times the frequency of the radio waves that are being eclipsed (Gedalin & Eichler 1993). Under the assumption that the outflow proceeds at about the orbital velocity (or somewhat higher), this implies a mass-loss rate of about 10^{13} g s^{-1}.

2. PHOTOSPALLATION AND LIGHT ELEMENTS

The photospallation cross section for $^{12}\mathrm{C} + \gamma \rightarrow {}^{11}\mathrm{B} + p$ becomes significant at photon energies above 15 MeV or so. It averages ~ 5 mbarn in the photon energy range 20–25 MeV, or ~ 1 mbarn per unit logarithm in photon energy at 20 MeV (Taran & Gorbunov 1967). Higher energy gamma rays and pairs that hit the companion surface cascade via bremsstrahlung pair-production cycles and always pass through this energy range. Shock acceleration of pairs followed by synchrotron emission would convert much of the shock energy to photons of about several MeV, so the amount of photospallation predicted by this scenario depends sensitively on a detailed calculation of the synchrotron spectrum.

We consider the consequences of the hypothesis that some fraction ϵ of the pulsar's spin-down power L arrives in the form of (or is converted to) 20 MeV photons. For convenience, we assume the average photon energy included in this fraction is 10^{-5} ergs. The hard photon flux incident on the companion is then $f = 3 \times 10^{14} f_{14.5}$, where $f_{14.5} = [\epsilon/(3 \times 10^{-3})] L_{35} D_{11}^{-2}$ photons cm^{-2} s^{-1}, L_{35} is L in units of 10^{35} ergs s^{-1}, and D_{11} is the orbital separation in units of 10^{11} cm. The lifetime of a C nucleus exposed to this flux is $\sim 3 \times 10^{12}/f_{14.5}$ s.

Can the outermost radiation length of material remain on the surface for more than 10^{10} s (in which case the heavy elements would be completely destroyed)? The mass-loss rate for the PSR 1957+20 system is conservatively estimated to be of order 10^{12} g s^{-1}, and could easily be 10^{13} g s^{-1} (so we define it to be $\dot{M}_{13}$ times this amount), from a surface area of $16\pi R_2^2 \times 10^{20}$ cm^2 (here R_2 is the radius in units of 2×10^{10} cm; $R_2 = 1$ corresponds to the case in which the companion to PSR 1957+20 fills its Roche lobe) or a stripping rate of at least $2 \times 10^{-9} \dot{M}_{13} R_2^{-2}$ g cm^{-2} s^{-1}. As a radiation length is $\sim 10^2$ g cm^{-2}, the stripping time could in principle exceed the lifetime of the heavy nuclei at the surface if there were no significant mixing of the surface layers, but it does not appear to exceed this lifetime by such a large factor that the spallation products themselves would be entirely broken down to He and H. Moreover, the observed absorption lines, insofar as they affect the continuum, are consistent with standard solar abundances (R. Romani 1994, private communication). We thus conclude that for PSR 1957+20, and similar systems, the spallation of heavy elements, if it occurs, does not defeat itself by the total destruction of either the heavy elements or the products. (Such destruction could in principle be important for some hypothetical range of parameters [high $f_{14.5}$, low $\dot{M}$, which would require suppressed mass evaporation by the radiation]. In this case, though, the destruction of primary heavy elements such as C would be the more conspicuous effect.)

Let us first suppose that all of the spallation products that are produced are eventually evaporated. This implies that the exposure time at the surface is determined by the mass-loss rate independently of convective mixing. By the above, the fraction of C that is spalled into lighter nuclei could be of order $1.5 \times 10^{-2} f_{14.5} [\dot{M}/(10^{13}\ \mathrm{g\ s^{-1}})]^{-1} R_2^2$, or unity, whichever is less. For PSR 1957+20–type parameters, this is many orders of magnitude above the cosmic values of Li, Be, and B. The largest change is in the abundance of B. The abundance levels depend on the cross sections of the reactions that produce and destroy the respective nuclei, the photon flux, and the exposure time. In the case of spallation that is just below the limit of total destruction of heavy nuclei, the ratios $^{10+11}$B/H, ^{9}Be/H, and ^{7}Li/H could be as high as 5.8×10^{-4}, 5.9×10^{-5}, and 3.7×10^{-6} (by number), respectively, after spallation (Boyd & Fencl 1991), compared to the cosmic ratios of 3.4×10^{-10}, 4.5×10^{-11}, and 2.3×10^{-9}, respectively (Cameron 1982). We have estimated these ratios for a photon number spectrum with an index of -2.7, assuming that the expected spectrum of PSR 1957+20 will be similar to that of the Crab Nebula (Nolan et al. 1993). These ratios change only slightly with the exact shape of the spectrum above 10 MeV. In any case, the spallation products should be above the otherwise expected levels if the incident flux of sufficiently hard gamma radiation on the companion is a small fraction (10^{-6} or more for PSR 1957+20) of the intercepted spin-down power. We suggest *Hubble Space Telescope* observations of the B I resonance lines near 2497 Å, which have been used to estimate the B abundances in halo stars (Duncan, Lambert, & Lemke 1992). Unfortunately, the reddening of PSR 1957+20 may make observations in the UV difficult, although this does not rule out the UV observations of other sources. The Li I resonance line at 6707.8 Å can be used to measure the Li abundance (as was done for V404 Cyg; see below).

The above neglects both dilution due to turbulent convection to deeper levels, which may occur more rapidly than the stripping time, and destruction by subvection to the core. In discussing this, it is useful to note that the column density of the entire star is $M/\pi R^2$, where M and R are respectively the mass and radius of the star, or $\sim 10^9$ radiation lengths. *If* the mass evaporation is such that all of the layer down to which the mixing occurs eventually is lost, then in steady state, the mixing has no effect on the level of spallation products at the surface. This includes the case in which the entire star is eventually evaporated. If, on the other hand, the mixing depth λ_m is larger than the time-integrated ablation depth λ_a (which grows linearly with time), then the dilution of spallation products is simply the ratio of the two, λ_m/λ_a. While an evaluation of the mixing depth is beyond the scope of this paper, we note that for PSR 1957+20 the layer of mass loss can be conservatively estimated from the dispersion measure of the eclipsing wind as 10^{12} g s^{-1} times the age t. For t of order of a spin-down time, which for this particular system is roughly a Hubble time or more, the lost mass is then $\sim 10^{-2}$ of the companion mass, so the astrophysical uncertainty imposed by our ignorance of turbulent mixing is not all that large. Even if the system is only $\sim 3 \times 10^7$ yr old, the uncertainty in λ_m/λ_a is several orders of magnitude less than the maximum light-element enhancement.

The light-element abundance in the gas that has been blown off from the companion is simply the ratio of the rate of accumulation of light-element nuclei to the stripping rate, apart from the dilution factor due to convection, as discussed in the previous paragraph. The rate of accumulation of light elements due to spallation has been calculated by Boyd & Fencl (1991). In the limit that neither C nor Li destruction is significant at the surface, we can use their calculations to express the abundances of light elements (for the case of $\lambda_m > \lambda_a$) as

$$\frac{\mathrm{B}}{\mathrm{H}} \sim \frac{\lambda_a}{\lambda_m} 8.5 \times 10^{-7} \dot{M}_{13}^{-1} R_2^2 f_{14.5} , \tag{1}$$

$$\frac{\mathrm{Li}}{\mathrm{H}} \sim \frac{\lambda_a}{\lambda_m} 10^{-8} \dot{M}_{13}^{-1} R_2^2 f_{14.5} , \tag{2}$$

$$\frac{\mathrm{Be}}{\mathrm{H}} \sim \frac{\lambda_a}{\lambda_m} 9 \times 10^{-13} \dot{M}_{13}^{-1} R_2^2 f_{14.5} , \tag{3}$$

where, as argued in the preceding paragraph, the ablation depth λ_a is a linear function of time and depends on the particular pulsar and its companion. Equations (1)–(3) show that the resulting B abundance in the companion can be very important even in the case of deep mixing, much more so than those of Li and Be. We note here that the ratio λ_a/λ_m for a companion mass of 0.02 $M_\odot$ can be written as $0.1 \tau_{10} \dot{M}_{13} R_m^{-1}$, where R_m is the mixing depth in units of R_2 and τ_{10} is the system's age in 10^{10} yr.

We have considered the possibility that spallation products are destroyed by nuclear burning. The companion star probably is too cool for this, if it fills its Roche lobe, in the case of

PSR 1957+20, where the companion mass is only 0.025 $M_{\odot}$ and the radius $\sim 0.3\ R_{\odot}$ (Fruchter et al. 1988). The central temperature is for these numbers only $\sim 1.5 \times 10^6$ K. In general, a light companion still on the main sequence could burn its spallation products; a star of 0.08 $M_{\odot}$, for example, has a central temperature of 4×10^6 K, enough for Li burning, which requires only 3×10^6 K (Swenson, Stringfellow, & Faulkner 1990), but clearly, even a modest amount of bloating would cool the companion's core too much to allow incineration of the spallation products. The case against incineration is even stronger for Be and B, and/or lighter companions, in cases such as PSR 1957+20, where the central temperature may not in general be enough for incineration under any set of assumptions.

3. V404 CYGNI

The Li abundance in the secondary in the V404 Cyg system has been estimateed to be of the order of Li/H $\sim 10^{-9}$, which is close to the cosmic interstellar ratio (Martin et al. 1992). This is anomalous in consideration of the facts that the secondary is most probably a G9 dwarf star (Martin et al. 1992) and that a G/K main-sequence star should be deplete its Li abundance by an order of magnitude after ~ 100 Myr and by 2–3 orders of magnitude after ~ 1 Gyr. In the light of the above discussion on photospallation, it seems possible that gamma radiation from the vicinity of the central object, a stellar-mass black hole, could easily reimburse the lost Li in the secondary star, as has been noted by previous authors (Martin et al. 1992; see also discussions on photospallation and light elements in other astrophysical contexts, e.g., Boyd & Fencl 1991; Gnedin & Ostriker 1992 [while Martin et al. 1992 proposed particle spallation in the accretion disk around the primary, spallation at the companion's surface should work just as well]). The near-cosmic observed abundance of Li requires a rough, coincidental balance between the production and destruction processes (at the present epoch) described by equations (1)–(3). However, there are two other possible reasons for the preservation of Li at roughly cosmic abundances that do not require such a coincidence.

First, it may be that heating of the companion's surface by the primary, compact object merely stabilizes the outer layers to convection so that the light elements in these layers are never subducted to the depths at which they are destroyed. Second, it may be that the black-widow effect, if the companion is destroyed on a timescale of ~ 10 Myr, selects out for observation only those systems that are too young to have suffered significant Li destruction. Theoretical analysis of the possibilities from first principles, in our view, are extremely difficult and not in any case the primary topic of this paper. Their viability depends, as for the case of pulsar companions, on the turbulence induced by horizontal pressure gradients that result from uneven heating of the surface. Such turbulence, together with heat conduction, competes with outward mass flow in determining the entropy distribution in the outer layers of the heated companion, and the matter is in our view not fully resolved. If the two "preservation" scenarios for the light elements can be observationally distinguished from the scenario of "restoration" by photospallation (the former predicting a higher ratio of ^{7}Li to the other light elements), though, then the results may have implications for the companions to pulsars as well.

4. CONCLUSIONS

Any model of companion irradiation by a primary pulsar in which quanta exceeding 15 MeV or so strike the companion's surface will predict that the companion's atmosphere is anomalously rich in Li, Be, and particularly B if the central temperature of the companion is too small to burn it. Spectroscopic observations of an ever-growing number of companions to binary pulsars may prove to be a powerful diagnostic of the high-energy output of the primary pulsar that is predicted theoretically.

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REFERENCES

Arons, J., & Tavani, M. 1994, ApJS, 90, 797
Boyd, R. N., & Fencl, H. S. 1991, ApJ, 373, 84
Cameron, A. G. W. 1982, in Essays in Nuclear Astrophysics, ed. C. A. Barnes, D. D. Clayton, & D. N. Schramm (Cambridge: Cambridge Univ. Press), 23
Duncan, D. K., Lambert, D. L., & Lemke, M. 1992, ApJ, 401, 584
Eichler, D. 1991, ApJ, 370, L27
Eichler, D., & Ko, Y.-K. 1988, ApJ, 328, 179
Eichler, D., & Letaw, J. R. 1987, Nature, 328, 783
Fierro, J. M., et al. 1995, preprint
Fruchter, A. S., et al. 1988, Nature, 334, 686
Gedalin, M., & Eichler, D. 1993, ApJ, 406, 629
Gilmore, G. 1992, Nature, 358, 108
Gnedin, N. Yu., & Ostriker, J. P. 1992, ApJ, 400, 1
Grove, J., Tavani, M., Purcell, W. R., Johnson, W. N., Kurfess, J. O., Strickman, M. S., & Arons, J. 1995, ApJ, 447, L113
Johnston, S., Manchester, R. N., Lyne, A. G., Bailes, M., Kaspi, V. M., Goujun, Q., & D'Amico, N. 1992, ApJ, 387, L37
Kluzniak, W., Ruderman, M., Shaham, J., & Tavani, M. 1988, Nature, 334, 225
Levinson, A., & Eichler, D. 1991, ApJ, 379, 359
Lyne, A. G., et al. 1990, Nature, 347, 650
Martin, E. L., Rebolo, R., Casares, J., & Charles, P. A. 1992, Nature, 358, 129
Nolan, P. L., et al. 1993, ApJ, 409, 697
Phinney, E. S., et al. 1988, Nature, 333, 832
Ruderman, M. A., Shaham, J., & Tavani, M. 1989a, ApJ, 336, 507
Ruderman, M. A., Shaham, J., Tavani, M., & Eichler, D. 1989b, ApJ, 343, 292
Swenson, F. J., Stringfellow, G. S., & Faulkner, J. 1990, ApJ, 348, L33
Taran, G., & Gorbunov, A. 1967, Soviet J. Nucl. Phys., 6, 816
Usov, V. V. 1983, Nature, 305, 409