NEW EVIDENCE ON THE SHAPE OF PULSAR BEAMS

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Abstract

From a study of the intensity and polarization data of a large number of pulsars, Lyne and Manchester (1988) showed that pulsar beams are essentially circular in cross-section, and confirmed that pulse widths are inversely correlated with pulse period. Using a homogeneous sub-sample of 80 "cone-dominated" pulsars from their compilation, we find an inverse correlation between pulse width and radio luminosity. We conclude that pulsar beams become wider at lower luminosities. This effect is expected since pulse profiles are observed to fall-off smoothly at their edges, thus showing that pulsar beams do not have sharp edges. If beams do become wider at lower luminosities, then some of the dispersion in the observed pulsar luminosities is not intrinsic, but merely due to varying offsets of the line-of-sight from the beam center. In view of this, one should re-examine the usual procedure of independently modeling the luminosity and beaming in pulsar statistics calculations. We expect that a self-consistent approach that includes luminosity and beaming within a single model will indicate that the "effective" beam size for statistical calculations is significantly larger (by a factor ~2) than the size one usually estimates based on the observed sample of high-luminosity pulsars.

Introduction

Gunn and Ostriker (1970) showed that the pulse width W (measured in degrees of phase) of the pulsars known at that time was inversely correlated with pulse period P with an approximate relation of the form $W = 14°P^{-0.3}$. They also pointed out that if the radio emission arises close to the neutron-star surface and is confined to the open field lines then one would have $W \propto P^{-1/2}$. Despite these arguments, for many years it was usual to assume a period-independent beam shape; in particular, the beaming fraction f defined to be the fraction of randomly-oriented pulsars potentially visible from earth, was assumed to have a constant value of 0.2, independently of P.

Narayan and Vivekanand (1982) used the Radhakrishnan and Cooke (1969) model of pulsar emission to analyze intensity and polarization data on 30 pulsars compiled by Manchester and Taylor (1977) and Backer and Rankin (1980). They concluded that W is relatively independent of P, but that beams are elongated meridionally, with a P dependent meridional beam-size, $W_{\mathrm{mer}} = 30°P^{-0.65}$. They obtained a P dependence in f, in agreement with Gunn and Ostriker (1970), but with a larger mean value and a steeper index of variation.

Lyne and Manchester (1988) collected together a large database of previously unpublished as well as new observations on about 160 pulsars and concluded the following:

1. W does vary with P; Narayan and Vivekanand had reached the opposite conclusion because several of their pulsars had profiles corresponding to partial cones and therefore erroneously small pulse widths.

2. There is no P-dependence of the polarization angle swing ψ showing that beams are more or less circular in cross-section; however, because of (1), the meridional beam size, and hence f, vary with P.

Lyne and Manchester proposed a model for the beam-width of the form $W = 13°P^{-1/3}$. Reanalyzing the same data, Biggs (1990) proposed that beams are *compressed* in the meridional direction, with $W_{\mathrm{mer}} = 10°P^{-1/2}$.

In view of the problem posed by partial cone profiles, we concentrate here on a sub-set of 80 "cone-dominated" pulsars in the Lyne and Manchester (1988) database. Lyne and Manchester claim that in these pulsars the emission beam is dominated by conal emission and that we see the full extent of the cone. The top panel in figure 1 shows $\log W$ plotted against $\log P$ for this homogeneous pulsar sample. We see that beams do become wider at shorter periods as claimed in many of the above studies. In the bottom panel we show $\log(WP^{0.5})$ *vs.* $\log P$ to demonstrate that a model of the form $W \propto P^{-1/2}$ fits the data reasonably well. In fact, the data suggest a slightly steeper power of P, but we restrict ourselves to the $W \propto P^{-1/2}$ model since it has some theoretical justification.

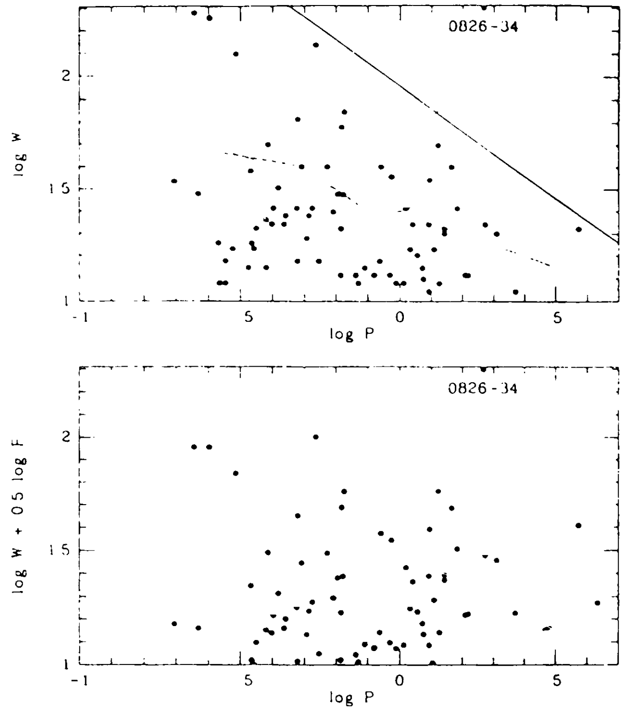

Figure 1 *Top panel*: $\log W$ *vs.* $\log P$ of 80 "cone-dominated" pulsars listed by Lyne and Manchester (1988). PSR 0826−34 has a listed W of 280°. The solid line shows mean W as a function of P in 4 bins of 20 pulsars each. The dotted line has a slope of −0.5. The dashed line (slope = −1) represents an apparent upper envelope.
Bottom panel: $\log(WP^{0.5})$ *vs.* $\log P$ of the same pulsars. Most of the trend in the top panel is removed in this scaling.

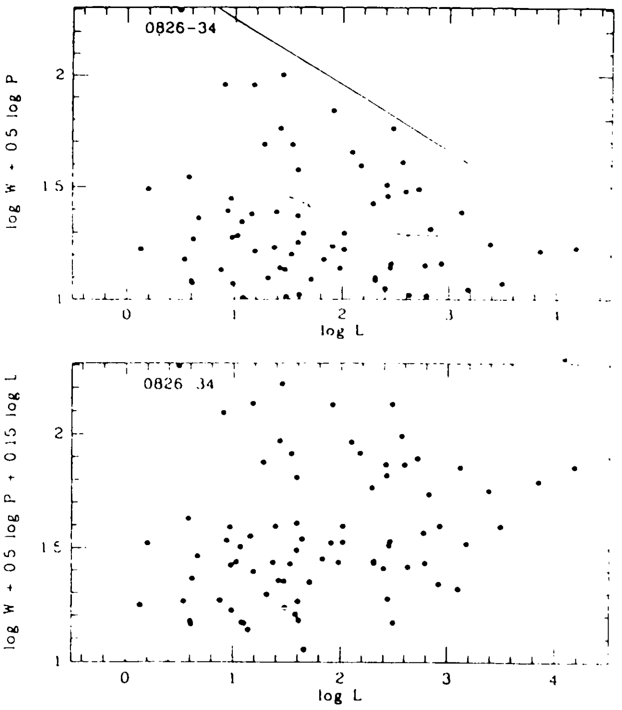

Figure 2 *Top panel*: $\log(WP^{0.5})$ *vs.* $\log L$ of the same pulsars as in figure 1. The solid line shows mean $WP^{0.5}$ as a function of L in 4 bins of 20 pulsars each. The dotted line has a slope of −0.15. The dashed line (slope = −0.3) represents an apparent upper envelope.
Bottom panel: $\log(WP^{0.5}L^{0.15})$ *vs.* $\log L$ of the same pulsars. Most of the trend in the top panel is removed in this scaling.

Pulse widths and radio luminosities

The new effect we wish to point out in this paper is shown in figure 2. We plot in the top panel of this figure $\log(WP^{0.5})$ *vs.* $\log L$, where L is the luminosity of the pulsar at 400 MHz in units of mJy kpc^2. The plot shows a rather convincing inverse correlation between $WP^{0.5}$ and L. An equally good correlation is obtained in a $\log W$ *vs.* $\log L$ plot, but we feel that it is more appropriate to scale out the known P dependence as we have done. Quantitatively, the correlation seems to be approximately of the form $WP^{0.5} \propto L^{-0.15}$. To demonstrate this we plot in the lower panel of figure 2 $\log(WP^{0.5}L^{0.15})$ *vs.* $\log L$. The correlation seen in the upper panel disappears almost entirely.

We have confirmed that the polarization angle swing ψ of the cone-dominated pulsars we have considered has no apparent correlation with $\log L$. Therefore, following the arguments of Lyne and Manchester (1988), it appears that beam circularity is preserved as a function of L. The results in figure 2 then imply that pulsar beams become larger at lower luminosities. This effect is quite natural since we know from the shapes of pulse profiles that the beam intensity does not cut-off abruptly at the beam edge, but falls off smoothly; in fact such an effect was anticipated by Sieber [see the discussion following the paper by Narayan (1986)]. The particular exponent 0.15 is hard to interpret, since in addition to the above effect, there is also doubtless an intrinsic dispersion in pulsar luminosities.

Effective beaming factor

An important consequence of the above result is that the beaming fraction f is not only a function of P, but also a function of L. The latter dependence introduces a new complication into pulsar statistics calculations. Normally, in such computations, one develops a luminosity model, $\phi(L)$, for pulsars and uses it to scale up the observed sample of bright pulsars to the galactic population of earth-beamed pulsars. The total number of pulsars, including those beamed elsewhere, is then obtained by multiplying further by $1/\bar{f}$, where $\bar{f}$ is the mean beaming fraction, suitably averaged over the pulsar P distribution. Because we now find f to be a function of L, this procedure has to be modified. The most straightforward approach is to absorb the beaming factor, along with its dependence on L, into the definition of the luminosity function, $\phi(L)$, and to scale up directly from the observed pulsars to the full galactic population.

Based on a rough calculation using the $W \propto L^{-0.15}$ law, we estimate that this procedure will lead to pulsar numbers and birthrates that are lower than the estimates without this scaling by a factor ~2. The reason for the reduction is straightforward. By our result, low-luminosity pulsars, which form the vast majority of the population, have much larger beams than bright pulsars. However, beam sizes are normally estimated from the *observed* sample, which is biased towards bright pulsars and hence smaller beams. The magnitude of the bias factor is ~2 according to our estimate. Thus, whereas the Lyne and Manchester (1988) estimate of beam size, $W = 13°P^{-1/3}$, gives a mean beaming fraction for the whole population of $\bar{f} = 0.2$, we suggest that a more appropriate factor, weighted over the galactic population, is $\bar{f} \sim 0.4$. Interestingly, the statistical calculations presented in Narayan and Ostriker (1990) are hardly affected at all. We had used the model of meridional beam elongation proposed by Narayan and Vivekanand (1982), which gives $\bar{f} = 0.38$. As we have seen, beams may not be elongated, but on the other hand they are effectively larger because of the correlation between W and L. The two effects fortunately cancel each other.

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