Pulsar Astronomy — 2000 and Beyond
ASP Conference Series, Vol. 202, 2000
M. Kramer, N. Wex, and R. Wielebinski, eds.

The Crab pulsar echoes

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Abstract. Observations over an eight month period from July 1997 to March 1998 show echoes following the radio pulses, and unusual changes in dispersion measure. We interpret this remarkable and complex event as refraction and dispersion in an ionised shell in the outer part of the Crab Nebula. The shell is remarkably compact; it has a electron density of about 10^3 – 10^4 cm^{-3} and a thickness of about 3×10^{11}m. Similar events have been noticed on several other occasions during the continuous monitoring of the Crab pulsar over the past 25 years.

1. The echoes

From July to October 1997 the routine recordings of the radio pulses from the Crab pulsar at 610 MHz showed distinct echoes following both the main pulse and the interpulse. The initial delay of 7 milliseconds decreased monotonically almost to zero in mid-October. The echo was well separated from the normal pulse, which appeared unaffected until the echo delay fell to zero. Over a period of 10 days centred on MJD 50753 the pulse weakened and disappeared, reappearing with a delay of 2.5 milliseconds. Observations at 1420 MHz showed that part of this delay was dispersive, following the frequency dependence expected from a change in propagation. The increase of 0.1 cm^{-3} in dispersion measure decayed to zero over the following 6 months.

A second echo, this time with an increasing delay, was observed in January 1998. Scrutiny of recordings over the past 25 years has revealed several similar echo events; in most cases the echoes appeared in pairs, first with a decreasing delay and then with an increasing delay. It seems likely that the echo in January 1998 should be paired with the August echo and was part of the same event. There was no step change in dispersion or rotational timing associated with this second echo.

Apart from the confusion between the original and the delayed pulse at the centre of the event, the pulse shape and the ratio of intensities of the three components were unchanged during the whole of this complex event.

There is a straightforward interpretation of the echoes and the changes in dispersion measure in terms of reflection and refraction in an ionised cloud close to the line of sight, and located within the Crab Nebula. The non-dispersive component of the delay can only be interpreted in terms of pulsar rotation; it is a confusing coincidence that the propagation and rotation events occurred nearly simultaneously. This paper is concerned only with the propagation phenomenon.

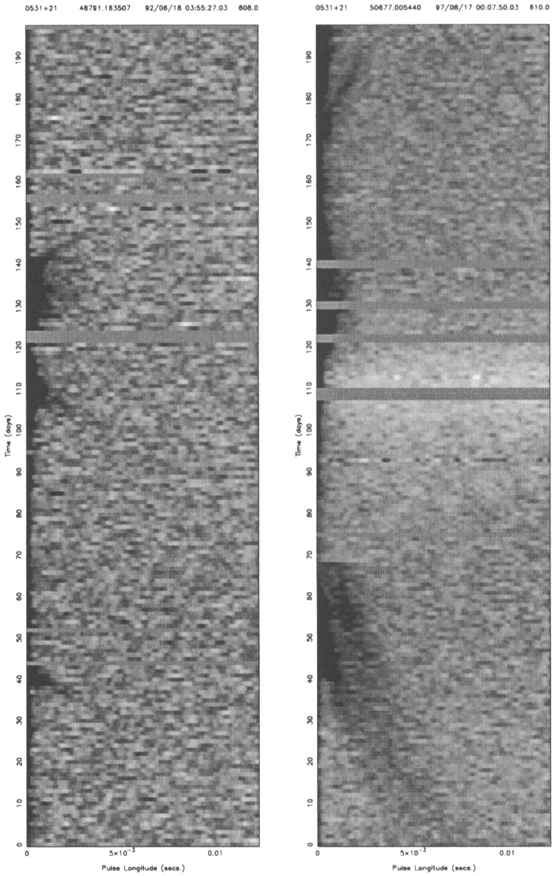

Figure 1. The echoes are shown separated from the normal pulse, using an origin which allows for the main timing effects including the effects of the glitch. Two sequences are shown, starting on 13/06/92 and 17/08/97.

In Fig. 1 the echoes are shown separated from the normal pulse. Two receding echoes can be seen, around MJD 50800 and 50860. Scrutiny of our recordings over the last 13 years shows several similar but previously unrecognised echoes. An example recorded in 1992 is also shown in Fig. 1 alongside the 1997/8 echoes.

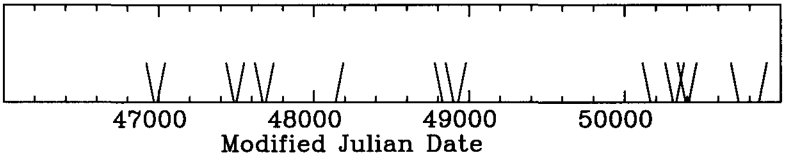

Figure 2. The chronology of observed echoes, distinguishing approaching and receding echoes.

The dates of these echoes are shown in Fig. 2 Approaching and receding echoes usually appear in a paired sequence similar to that in 1997/8. The phenomenon recurs at intervals of several years. No association with steps in delay, either dispersive or non-dispersive, has been observed on these previous occasions. In 1974 Lyne and Thorne (1975) observed a large scattering event in the Crab pulsar; the structure of the scattered profile apparently contained discrete moving components, and we now regard this as a further example of an echo.

2. Dispersion

Pulse arrival times are routinely monitored daily at 610 MHz, and less frequently at 1420 MHz. Standard templates are used to find the arrival times of pulses; arrival times are routinely corrected to the barycentre of the solar system, and fitted to a rotational model, using values of rotation rate and slowdown rate determined from observations made over some months before the event. The times for the two frequencies coincide after allowing for a change in dispersion measure (DM) which increased around MJD 50753 from 56.800 to 56.900 pc cm^{-3}.

The dispersion measure was monitored closely until May 1998, by making more frequent observations at 1420 MHz for comparison with the lower radio frequencies. The DM shows nearly linear decline, almost recovering its pre-event value over a period of 250 days.

3. The reflecting electron cloud

Assuming that the line of sight was at distance x from the reflector when the echo delay was 7 ms, and treating the echo as a purely geometric delay due to an extra path $d = 2 \times 10^6$ m , we can find the distance $R = x^2/2d$ of the reflector from the pulsar. The pulsar has a transverse velocity of 100 km s^{-1} (Wyckhoff and Murray 1977), moving a distance $x = 5 \times 10^{11}$ m in two months.

The distance R is then 6×10^{16} m, or 2 parsecs, which is the radius of the Crab Nebula.

The angular deviation of the reflected ray x/R is 2 arcseconds. The reflection occurs at an ionised sheet at a glancing angle of incidence $\alpha = x/2R$. The turning point of the ray occurs where the refractive index $1 - \epsilon = \cos \alpha/2$, giving $\epsilon = \alpha^2/8$. Since $\epsilon = 8 \times 10^{-5} n_e/\nu^2$, where n_e is electron density (cm^{-3}) and ν is radio frequency (MHz), we find that all radio frequencies are reflected by an electron density less than 1 cm^{-3}. This must be at the outside of the shell, inside which much greater densities are found. The echo delay is dominated by the geometric path, with very little dispersive component from propagation through the increased electron density.

The step increase of 0.1 cm^{-3} in dispersion measure must represent a ray passing tangentially through the shell. The shell thickness is of order 10^{11} m (close to 1 AU), as estimated from the time during which the pulses were lost or much scattered. We can guess at a path length of 3×10^{12}m, with $n_e = 10^3$ cm^{-3}. The decrease in excess DM over a period of 6 months is consistent with propagation through a thin hollow shell; the path through a uniform spherical shell would decrease by a factor 10 when the line of sight had moved by 25 times the shell thickness.

4. Conclusion

The echoes and the dispersive delay are accounted for in terms of a single ionised shell located within the Crab Nebula. At the highest angular resolution of Hubble Space Telescope (about 0.2 arcseconds) there is an unresolved fibrous or 'brush-stroke' structure to be seen over much of the Crab Nebula (Hester et al 1997). The thickness of the ionised shell which we now observe is two orders of magnitude smaller; furthermore the frequent occurrence of echoes suggests that the Nebula is filled with many such shells.

References

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