Echoes of Giant Pulses from the Crab Pulsar

J. H. Crossley, J. A. Eilek and T. H. Hankins

New Mexico Tech, Socorro NM, USA

Abstract. We have detected occasional, short-lived “echoes” of giant pulses from the Crab pulsar. These echo events remind us of previously reported echoes from this pulsar, but they differ significantly in detail. Our echo events last at most only a few days; the echo emission lags the primary emission by only $40 - 100 \mu$s. The echoes are consistently weaker and broader than the primary emission, and appear only at the lower of our two simultaneous observing frequencies. We suggest that these echoes are created by refraction in small plasma structures — plasma clouds or magnetic flux ropes — deep within the Crab nebula. If this is true, our echoes provide a new probe of small-scale structures within the inner synchrotron nebula.

Our group has been working to understand the physics of the pulsar emission region. To that end, we have pursued high time resolution observations, because differences in the physics should lead to different time signatures in the radio emission. We have concentrated on the Crab pulsar, because its occasional very bright “giant” pulses are well suited to our data acquisition systems. The results we report on here come from a VLA program to observe single pulses from the star at sub-$\mu$s time resolution.

The pulsar sits at the heart of the Crab Nebula — which is, of course, powered by spindown of the pulsar. The complex nebular structure includes the relativistic pulsar wind; the shock ($\sim 0.1$ pc from the pulsar) at which the cold wind is thermalized; the highly variable “wisps” and “knots” associated with the dynamic, post-shock region (Hester et al. 2002; Bietenholz et al. 2004); the diffuse synchrotron nebula ($\sim 0.1 - 1$ pc from the pulsar), which is thought to contain shocked wind plasma; and the cool, filamentary outer regions (emitting optical emission lines and radio bremsstrahlung), which may be due to Rayleigh-Taylor instabilities at the interface between the synchrotron nebula and the stellar ejecta.

Because our interest was in the pulsar itself, we initially saw the nebula mostly as a nuisance. Its high sky brightness makes observations of fainter pulsar signals challenging; its internal “weather” has long been known to cause fluctuations in dispersion, Faraday rotation and scattering broadening of low-frequency pulses. We were surprised, then, to notice that our high-frequency, high-time resolution observations had detected what we think is a new type of nebular weather: small (AU-size), dense fluctuations within the nebular synchrotron plasma. In this paper we summarize our observations and our suggested interpretation; we give more details in Crossley, Eilek & Hankins (2007).
1. Observations: echoes of the giant pulses

We used the VLA to record single pulses from the Crab pulsar on 20 observing days between 1993 and 1998, with a 50-MHz bandwidth centered at 1.4 or 4.9 GHz. Some days we split the VLA into 2 subarrays to record both frequencies simultaneously. A typical giant pulse contains one to several short-lived microbursts, which last \( \sim 10 \mu s \) at 1.4 GHz, and are shorter at 4.9 GHz (e.g., Hankins 2000). These microbursts generally seem to be random, in rotation phase and amplitude, suggestive of unrelated flare events in the radio emission region. However, a different pattern emerged on two observing days. A bright “primary” burst at 1.4 GHz is followed \textit{in nearly every recorded pulse} by a fainter, broader “echo” burst; the same pulse at 4.9 GHz shows no echo. Figure 1 shows three example pulses. The echo properties, relative to the primary, remained constant for the full duration of each day’s observing run (32 clear echoes within 3 hours on one echo-event day; 9 clear echoes within 15 minutes on the other day). The unusual consistency of the echo properties during each observing day leads us to suggest these echoes are not intrinsic to the star, but rather are due to some chance structure in the nebular plasma which happened to lie along the line of sight on those days.

![Figure 1](image-url) Three giant pulses from the Crab pulsar, recorded simultaneously at 1.4 and 4.9 GHz within two hours at the VLA, and displayed with 2-\( \mu s \) time resolution. The top row shows the pulses at 1.4 GHz; echo emission following the primary pulse by \( \sim 50 \mu s \) is apparent. The bottom row shows the same three pulses, but now at 4.9 GHz, where no echoes are seen. The smooth, light lines on the 1.4-GHz pulses are the component fits we used to measure arrival times, widths and energies of pulse components.
In order to quantify our results, we fit individual microbursts with the function $I(t) = A(t - t_o)e^{-(t - t_o)/\tau}$. This enabled us to determine the component arrival time ($t_o$), width ($\propto \tau$), peak flux ($\propto A\tau$), and energy content ($E = A\tau^2$). The echo properties we derive are remarkably uniform within each echo-event day. The echoes are broader: $\tau_{echo}/\tau_{primary} \sim 2.5$ on one echo-event day, $\sim 4.6$ on the other day. The echoes are fainter: the peak echo flux $\sim 10\%$ of the peak primary flux, on both echo-event days. Their energy ratio is $E_{echo}/E_{primary} \sim 0.25$ on one day, and $\sim 0.35$ on the other day. Their time lag, relative to the primary, is $\sim 45\mu s$ on one day, $\sim 90\mu s$ on the other day. On both echo-event days, we see the echoes clearly at 1.4 GHz, but not at 4.9 GHz. We also observed the pulsar two days before and two days after the first echo-event day, without seeing any echoes. We can thus bracket the duration of this echo event: it lasted between three hours and four days.

2. Interpretation: small structures in the Crab Nebula

Our echoes are reminiscent of similar events reported by other authors. Lyne, Pritchard & Graham-Smith (2001) reported 10 such events, detected in time-averaged mean pulse profiles at 610 MHz. One particularly dramatic event was analyzed in detail by Lyne et al. (2001), and also by Backer, Wong & Valanju (2000). If this particular echo event is characteristic of all reported by Lyne et al., these previous echo events differ quantitatively from ours. They last much longer (several tens of days), during which the echo lag changes smoothly between several milliseconds and the time resolution of the observations ($\sim 1\text{ ms}$). The echoes often appear to approach the primary, then recede from it. These previous echoes are achromatic; they have the same characteristics at 327 and 610 MHz (reported by Backer et al. 2000). At least one echo event coincided with a significant jump in dispersion measure, $\Delta(DM) \sim 0.1\text{cm}^{-3}\text{pc}$. Backer et al. (2000) and Lyne et al. (2001) modeled this event as refraction or reflection from a dense plasma structure related to the cool filaments in the outer regions of the Crab nebula.

By contrast, our echo events are shorter-lived, have a much shorter time lag, and are frequency dependent. Can they be explained by something similar? We first note that the $\sim 50-100-\mu s$ echo lag must be due to a longer propagation path. If the time lag were dispersive, $\propto 1/\nu^2$, we would expect to see similar strength echoes with 4 to 8-\mu s lags at 4.9 GHz. No such echoes were found, either in direct inspection of individual pulses, or in autocorrelation analysis. We therefore conclude that the echo time lag is geometrical, due to the echo path length being $\sim 15-30\text{ km}$ longer than that of the primary.

Because the time delay is geometrical, and the echo is only seen at the lower frequency, we hypothesize that the 1.4-GHz echo is due to reflection from some plasma structure within the nebula. We envision this structure as a dense plasma cloud in a turbulent region, or possibly dense plasma within a magnetic flux rope. We note that “reflection” in this context should be interpreted as total internal reflection, caused by refraction when the signal propagates into a higher density plasma. The lack of any echo at 4.9 GHz must mean the density in the plasma structure is not high enough to reflect that frequency. If the reflecting structure is at a distance $R$ from the pulsar, and the beam deflects by angle $\theta$,
a 50-μs lag requires $\theta^2 R \sim 30$ km. We do not know $R$, but if our feature is associated with the nebular synchrotron plasma, we expect $0.1 \text{ pc} < R < 1 \text{ pc}$. If the duration of the echo event is due to a plasma cloud moving across the line of sight, the transverse size of the cloud must be no more than an AU.

We also recall that full reflection occurs if the incident angle, $\delta$, relative to the surface of the reflecting structure, satisfies $\delta \leq \nu_p/\nu$ (where $\nu_p$ is the plasma frequency; this assumes the cold plasma dispersion law, and small angle approximations). If we combine this condition with the time delay, we can bracket the density of the reflecting feature: $0.003 \text{ cm}^{-3} < n < 0.4 \text{ cm}^{-3}$. (If the plasma is internally relativistic, with mean particle energy $\gamma mc^2$, $n$ in our result should be replaced by $n/\gamma$; e.g., Wills & Cairns 2000). The other properties of our echoes also seem to fit this picture. If the plasma within the reflecting structure is itself turbulent, multipath propagation will broaden the echo relative to the primary. If the surface of the reflecting structure has some curvature, dispersion of the reflected beam will cause the echo to be weaker than the primary.

Can our speculation be tested? The density range we require for such plasma clouds is well below that estimated for the cool, outer filaments. Where might AU-sized features with this density range exist within the Crab Nebula? We think the most likely place to find such features is the diffuse synchrotron nebula, which is almost certainly turbulent and inhomogeneous (probably filamented into disordered magnetic flux ropes, as Hester et al. 1995 point out). We note that, in addition to the ordered, elliptical ripples (“wisps”) seen close to the pulsar, a fair amount of faint, disordered structure is apparent in the images (e.g., Bietenholz et al. 2004). We suspect this is the “tip of the iceberg” of the turbulence; but such structures are hard to quantify. The most sensitive observations to date are those from HST (Hester et al. 1995). If we apply standard (equipartition) synchrotron analysis to the smallest, highest-emissivity knot they report, we find the plasma density in that knot may just be consistent with our required density range. We also note that our estimates have a fair amount of “wiggle room”. We fully expect smaller, denser features to exist below HST’s sensitivity and resolution; and we recall that equipartition is only an approximation to the true state of the plasma. We therefore conclude that the sources of our echoes are likely to be dense, transient clouds or flux ropes in the turbulent synchrotron plasma within the Crab Nebula.

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