Kinematics of Crab Giant Pulses

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Overview

First Direct Measurement
Lorentz Factor

\[ \gamma \sim 10^4 \]
Highly Relativistic motion
Relatively cold plasma

Theoretical Predictions

\[ \gamma = 1 - 10^7 \]
Introduction: Crab Nebula & Pulsar

Remnant of SN 1054

PSR B0531 +21
Giant Radio Pulse Behaviour

Can reach brightness temperatures of $10^{37}$ K

Jessner et al. 2005

Bochenek et al. 2020

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Variations in electron density $n_e$ of size $a$

Phase shift

$$\delta \Phi = \Delta k \ a$$

$$k = \left(\frac{2\pi}{c}\right) \mu \ f$$

Model as bending by screen

$$\theta_0 \approx \frac{\Delta \Phi / k}{a} \propto f^{-2}$$

Frequency dependent
Scattering in Observations

\[ c \tau_s = \frac{d}{\cos \delta} - d \]

\[ \delta \propto f^{-2} \]

\[ \tau_s \approx \frac{\delta^2 d}{2c} \]

\[ \tau_s \propto f^{-4} \]
Crab Giant Pulses at High frequencies

"nanoshot" emission

Hankins et. al 2016
1-43 GHz

"spectral band" emission
Pulse Gallery and Categorization

Regular

Double-Peak

Partial

Banded

Drifting
Observed shifts in frequency
Ruling out other interpretations

Instrumentation effect?

Scattering Environment?

Scintillation?

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Observed shifts in frequency
Proposed Model – Doppler Shift

Doppler Shift

\[ D = \frac{f_r}{f_s} = \frac{1}{\gamma (1 - \beta \cos \theta_r)} \]

\[ \beta = \frac{v}{c} \]

\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]

Relativistic Beaming

\[ L_r = D^3 L_s \]

Small Angle Approximation

\[ D = \frac{f_r}{f_s} \approx \frac{2\gamma}{1 + \gamma^2 \theta_r^2} \]

\[ \gamma \gg 1 \]
Proposed Model – Doppler Shift + Scattering

\[ D = \frac{f_r}{f_s} \approx \frac{2\gamma}{1 + \gamma^2 \theta_r^2} \]

Scattering from Crab Nebula

\[ \frac{\Delta f_r}{f_r} = \frac{\Delta D}{D} = -\gamma^2 \frac{2\theta_r \delta + \delta^2}{1 + \gamma^2 (\theta_r + \delta)^2} \]

Center of beam

\[ \theta_r \approx 0 \quad \Delta f_r / f_r \approx -\gamma^2 \delta^2 \]

Edge of beam

\[ \theta_r \approx 1/\gamma \quad \Delta f_r / f_r \approx \gamma \delta \]
Proposed Model – Estimating Lorentz Factor

\[ \frac{\Delta D}{D} = \frac{\Delta f_r}{f_r} \approx \gamma \delta \]

\[ c\tau = \frac{d}{\cos \delta} - d \simeq \frac{d}{2} \delta^2 \]

\[ \tau \simeq 0.5 \text{ ms} \]
\[ \delta \simeq 0.6'' \]

\[ \frac{\Delta f_r}{f_r} \simeq 0.04 \]

\[ \gamma \approx 10^4 \]

\( d \approx 1 \) pc

(Lawrence et al. 1995, Martin et al. 2021)
Does the model match the data?

\[ \Delta f_r \approx \gamma \delta \quad \delta \propto \sqrt{t} \]

\[ \frac{\Delta f_r}{f_r} \propto \sqrt{t} \]

\[ I(t, f) = I(0, f/D_{rel}(t)) \cdot D_{rel}^3(t) \cdot e^{-t/\tau(f)} \]

\[ D_{rel}(t) = \frac{D(t)}{D(0)} = 1 + a \sqrt{t/\tau_{ref}} \]

\[ \tau(f) = \tau_{ref}(f/f_{ref})^{-4} \]

\[ a \approx 0.028 \]
Does the model match the data?

\[ I(t, f) = I(0, f/D_{\text{rel}}(t)) \ D_{\text{rel}}^3(t) \ e^{-t/\tau(f)} \]
Proposed Model – Range in Lorentz Factor

\[ \frac{\Delta D}{D} = \frac{\Delta f_r}{f_r} \approx \gamma \delta \]

\[ \gamma \approx 10^4 \]

\[ \Delta \nu \approx 20 \text{ MHz} \]

\[ \Delta \gamma / \gamma \lesssim \Delta \nu / \nu \approx 4\% \]

Relatively cold plasma
Alternative Interpretations

Interference between multiple nanoshots

\[ x_{\perp} \delta \approx 0.5\lambda \]
\[ \lambda \approx 0.5 \text{m} \]
\[ \delta \approx 0.6'' \]
\[ x_{\perp} \sim 100 \text{km} \]

Figure Credit: Wenbin Lu
Implications + Model Predictions

- Different scattering geometries – upward + downward drift
- Small range in $\gamma$ – cold plasma
- Boost in intensity in scattering tail by $\sim 10\%$
- Physical separation 20 lt-ns
Implications for FRBs?

Hessels et al. 2019

CHIME 2019

DM=349.1

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Crab Giant Pulses at High frequencies

Hankins et. al 2016

1-43 GHz
Next Steps

• Look for more “drifting” pulses – CHIME, LOFAR

• Lower frequency data where change in viewing angle is larger

• Downward drift or boosting?

• Statistical analysis of giant pulse characteristics

• FRBs with large scattering
Summary

Crab Pulsar

400-800 MHz

Doppler Shift

Scattering screen

Lorentz Factor

Direct Measurement

\[ \gamma \sim 10^4 \]

Theoretical Predictions

\[ \gamma = 1 - 10^7 \]
Thank you!
Any questions?
$F_{GP}(f) = F_{neb}(f) \frac{I_{GP}(f)}{I_{neb}(f)}$
Table 1. Giant pulse categorization.

| Feature     | \( N \) | Fraction (%) | IP (%) |
|-------------|---------|-------------|--------|
| All         | 148     | 100         | 10     |
| Regular     | 129     | 87          | 10     |
| Multi-peak  | 9       | 6           | 0      |
| Partial     | 7       | 5           | 30     |
| Banded      | 3       | 2           | 0      |
| Drifting\(^a\) | 2     | 1.3         | 0      |

\(^a\) ‘Drifting’ is a sub-category of ‘Banded’.

NOTE—\( N \) is the number of pulses that have a given feature, fraction the relative occurrence rate, and IP is the fraction that occurred in the interpulse phase.
Appendix - Ruling out other physical interpretations

- Interplanetary Scintillation
  - Expected De-correlation bandwidth 500 MHz

- Interstellar Scintillation
  - Expected De-correlation bandwidth 30 kHz
  - Not a point source
Appendix: Drifting Pulse Before de-dispersion