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FAST SINUSOIDAL OSCILLATIONS IN THE RADIO FLUX OF GRS 1915+105

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ABSTRACT

We report the observation of events with fast (≤1 hr) time variability in Very Large Array observations of the Galactic superluminal source GRS 1915+105. The database consists of observations made at 67 epochs over 3 yr. We have detected fast variations on three occasions. Here we report the most remarkable of the events, observed in 1995 September 6. Over a period of approximately 2 hr, the 3.6 cm flux density of GRS 1915+105 showed several clear sinusoidal oscillations with period of 30.2 ± 0.4 minutes, going from ∼40 to ∼65 mJy. We discuss possible scenarios for the production of this fast sinusoidal variation in the radio flux density and propose that the variability could be the result of a hot spot orbiting the collapsed companion of the binary system.

Subject headings: radio continuum: stars — X-rays: stars

1. INTRODUCTION

The Galactic superluminal source GRS 1915+105 (Mirabel & Rodríguez 1994) is known to undergo strong radio and X-ray outbursts, with the ejection of twin plasma clouds at relativistic speeds (Mirabel et al. 1996a; Harmon et al. 1997). The centimeter radio flux is believed to be of synchrotron nature and is known to exhibit large variations on a timescale of several hours or days (Rodríguez et al. 1995). At least in part, these variations are known to be the result of the ejection of expanding plasma clouds.

However, there is also evidence that at some epochs the radio emission is dominated by a very compact component with flux density in the range of tens of millijanskys. Presumably, this emission originates at or very close to the binary system. Observations made at the Very Large Array (VLA) (Rodríguez & Mirabel 1996) and the Ryle Telescope (Pooley 1995, 1996) indicate that this component can vary on timescales below 1 hr and can even exhibit quasi-periodic oscillations (Pooley 1995, 1996). In this Letter, we present the detection of a remarkable event, in which the flux density of GRS 1915+105 exhibited a clear sinusoidal variation for which several oscillations were detected over a period of about 2 hr.

2. OBSERVATIONS

The observations were carried out using the VLA of NRAO[1] at 67 epochs between 1993 April 27 and 1996 April 22. Most of the data were taken at 3.6 cm. On all occasions, the phase calibrator was 1923+210. The data were edited and calibrated using the software package AIPS of NRAO. We searched for time variability by analyzing the real and imaginary components of the visibilities as a function of time.

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

3. FAST TIME VARIABILITY EVENTS

We have detected fast (≤1 hr) variations on three occasions, out of the 67 epochs observed. This result suggests that the source is undergoing detectable fast variability about 4% of the time.

The first event took place on 1994 November 16 and was reported in Rodríguez & Mirabel (1996). On that occasion, the 3.6 cm flux density rose by a factor of 5, from 8 to 40 mJy, in about 10 minutes. Using light-travel time arguments, Rodríguez & Mirabel (1996) proposed that the radio continuum emission from the core probably originates from a region with dimensions comparable to or smaller than $\sim 10^{13}$ cm. If this estimate is correct, the brightness temperature during this event reached at least $T_B \simeq 5 \times 10^{11}$ K, implying that the brightness could have been inverse-Compton limited.

The second event of fast variability took place on 1995 August 10 near the peak of a strong radio outburst, studied in detail by Mirabel et al. (1996b). About 4 hr after the maximum emission observed with the Green Bank Interferometer (Foster et al. 1996), we carried out VLA observations of GRS 1915+105 at 3.6 cm. During the first 15 minutes of the observations in this VLA run, the source showed a constant flux density of 431 ± 2 mJy. However, 30 minutes later, when the observations of other sources had finished and the observations of GRS 1915+105 were resumed, we found that the flux density of GRS 1915+105 had dropped by 16 ± 3 mJy to 415 ± 2 mJy, and it remained constant at that value until the end of the observations 15 minutes later. This behavior may suggest that during flares part of the decrease in the flux density may take place in discontinuous steps.

As part of the follow-up campaign to the 1995 August 10 burst, we made observations on three more occasions: 1995 August 17 and 24 and September 6. These observations were made with the VLA in its A configuration, that of highest angular resolution (0.″2 at 3.6 cm). The source appeared as unresolved at all epochs. While in 1995 August 17 and 24 the flux density of the source had dropped to 3.1 and 0.1 mJy, respectively, we noted an increase to the 50 mJy level for

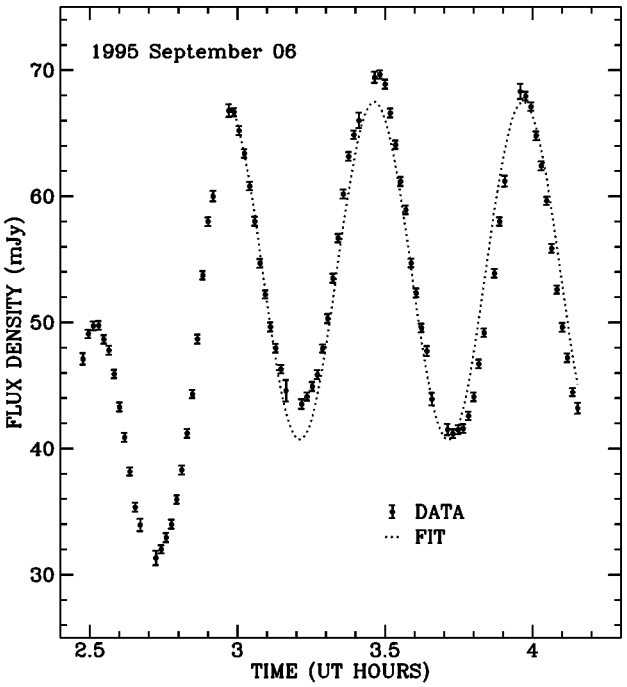


FIG. 1.—Flux density of GRS 1915+105 at 3.6 cm as a function of UT hours for 1995 September 6. Integration time per data point is 1.3 minutes, and typical 2 σ rms error bars are 0.3 mJy. The dotted line is a least-squares fit to the last 2.5 cycles (data after 2.95 hr UT), made using a sine function.

September 6. Detailed analysis of these data revealed the remarkable sinusoidal variation in the flux density shown in Figure 1.

We also analyzed these observations for polarization. On average, the source has a linear polarization of 0.8% ± 0.1%, with position angle of 40° ± 10°. In the context of optically thin synchrotron emission, this result can be interpreted to imply that close to the binary system the magnetic field is probably parallel to the direction of the jets, which have a position angle of 140° ± 10° (Mirabel & Rodríguez 1994), whereas at distances $\geq 10^{16}$ cm from the source, the magnetic field has been observed to be perpendicular to the direction of motion of the relativistic ejecta (Rodríguez et al. 1995). However, as discussed below, the sinusoidally varying emission could have a nature other than synchrotron, and the inferences regarding the orientation of the magnetic field are not necessarily correct. For the circular polarization, we obtained an upper limit (3 σ) of $\leq 0.2\%$. As a function of time, both the linear polarization and the position angle appear to show some evidence of modulation. However, the signal-to-noise ratio of these parameters is not great enough to reach a solid conclusion.

4. DISCUSSION

The flux densities illustrated in Figure 1 show a first cycle whose maximum flux density is less than those of the oscillations that followed. We have made a least-squares fit of the last two and one-half cycles (that is, the data taken after 2.95 hr UT) to a sine function. The period of the oscillations shown in Figure 1 is 30.2 ± 0.4 minutes.

Oscillations of similar nature (but observed with smaller signal-to-noise ratio because of the relative weakness of the sources) have been reported in V404 Cygni and in LSI +61°303 (Han & Hjellming 1992; Peracaula, Martí, & Paredes 1996). It is interesting that, in all three sources, the periods of the radio continuum oscillations are in the range of tens of minutes, suggesting a common mechanism. Both Han & Hjellming (1992) and Peracaula et al. (1996) have suggested that the oscillations could be the result of the compressions produced by a set of shocks propagating in an inhomogeneous jet. However, the smoothness of the light curve shown in Figure 1 appears to favor a mechanism without strong discontinuities.

We believe that the remarkable smoothness and periodicity of the oscillations observed in GRS 1915+105 suggest that they are related to rotation. However, we can rule out effects associated with the period of the binary or rotation of a neutron star because, in these cases, the period would repeat in different observations, while in GRS 1915+105 they do not repeat (although the observed periods remain in the range of tens of minutes, as discussed below). Fast quasi-periodic variations have been seen in two later epochs: 1995 December (Pooley 1995) and 1996 May (Pooley 1996), with periods of 38 and 22 minutes, respectively. It appears highly unlikely that the orbital period of a binary system could change significantly in a time interval of only a few months. The nonrepeatability of the period rules out mechanisms related to binary orbital periods or other phenomena with approximately fixed periods, such as a possible slow pulsar.

We believe that the observed periodicity could be related to the presence of a hot spot orbiting the collapsed companion. The hot spot could result from discontinuous accretion of mass or from instabilities in the disk, producing regions of enhanced density. This mechanism could produce, at a given event, a certain reasonably fixed period; but, in events at other epochs, a newly formed hot spot could be located at different radii, giving a different period. A period of 30 minutes will be observed for gas rotating at a radius of $2 \times 10^{10}[M_c/(1\ M_\odot)]^{1/3}$ cm from the collapsed companion. Since the period is well defined, the size of the emitting hot spot must be significantly smaller that the radius of about 2×10^{10} cm, leading to brightness temperatures of order 10^{16} K, far in excess of the Compton limit of $\sim 10^{12}$ K. As in the case of pulsars, a coherent emission mechanism appears to be required. It is possible that the hot spot, being illuminated by the central source, emits coherently by stimulated Raman scattering (Levinson & Blandford 1995).

The sinusoidal variation can be explained tentatively as follows: Assume that the disk is embedded in an envelope of ionized gas. This gas will absorb radiation via free-free opacity. As the emitting region rotates around the collapsed companion, it will appear to the observer to move inside this ionized envelope to later emerge, with the amount of ionized gas in the line of sight to the spot varying cyclically. If we assume the envelope to be homogeneous, it is easy to show that the intensity of the source will be modulated by the following expression:

$$I = I_0 \exp\left[-\tau(1 - \cos \omega t)/2\right],$$

where I is the observed intensity at time t, I_0 is the intensity when the emitting region is closest to the observer, τ is the maximum opacity (when the emitting region is at its most distant position from the observer), ω is the angular frequency, and t is the time ($t = 0$ when the emitting region is closest to the observer). As long as the opacity remains small ($\tau \leq 1$), the above expression can be approximated by

$$I \simeq I_0[1 - (\tau/2) + (\tau/2) \cos \omega t].$$

Then the periodic sinusoidal variations in the intensity of the source can be explained by the motion of the hot spot in the ionized envelope. In the context of this hypothesis, the orbital plane of the hot spot must have a certain inclination with respect to the line of sight. Since, for the observed variability, τ would have to be about 0.5 at 3.6 cm, an emission measure of $\sim 10^{11}$ cm^{-6} pc is obtained—assuming an electron temperature of $\sim 10^6$ K. An electron density of $\sim 10^9$ cm^{-3} is then derived for the ionized envelope. This simple model can be tested directly with simultaneous, multifrequency observations of a new oscillation event. Since free-free absorption varies as wavelength squared, the oscillations should be increasingly evident for the longer wavelengths. It should be noted, however, that there are other geometries that can account for the variability. For example, bright, constant emission from the immediate vicinity of the collapsed object could be modulated by absorption in an inhomogeneous rotating disk.

5. CONCLUSIONS

The quasi-periodic oscillations observed in the radio band in GRS 1915+105 suggest the existence of hot spots orbiting the collapsed companion at radii of a few times 10^{10} cm and periods of a few tens of minutes. The brightness temperature of these synchrotron-emitting regions is of order 10^{16} K, and as in the case of pulsars, a coherent emission mechanism appears to be required.

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