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Discovery of a High-Energy Gamma-Ray-Emitting Persistent Microquasar

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Microquasars are stellar x-ray binaries that behave as a scaled down version of extragalactic quasars. The star LS 5039 is a new microquasar system with apparent persistent ejection of relativistic plasma at a 3 kiloparsec distance from the sun. It may also be associated with a γ-ray source discovered by the Energetic Gamma Ray Experiment Telescope (EGRET) on board the COMPTON-Gamma Ray Observatory satellite. Before the discovery of LS 5039, merely a handful of microquasars had been identified in the Galaxy, and none of them was detected in high-energy γ-rays.

The $V = 11.2$ magnitude star LS 5039 (*1*) has been recently identified as a nearby high-mass x-ray binary with spectral type O7V((f)) (*2*) and persistent radio emission (*3,4*). Here, we report high-resolution radio observations with the Very Long Baseline Array (VLBA) and the Very Large Array (VLA) that reveal that LS 5039 is resolved into bipolar radio jets emanating from a central core.

Because LS 5039 appeared unresolved ($\leq 0.1''$) to the VLA alone, we proceeded to study this object with milliarc sec resolution using the VLBA at the frequency of 5 GHz (6 cm wavelength) on 8 May 1999. The VLA in its phased array mode, equivalent to a dish of 115 m diameter, also participated as an independent station, providing sensitive baselines with the VLBA antennas. The source 3C345 was used as a fringe-finder, whereas J1733−1304 was the phasing source for the VLA. The data were calibrated using standard procedures in unconnected radio interferometry. The resulting pattern of the observed visibility amplitudes, decaying as a function of baseline length, indicated that LS 5039 had structure at milliarc sec scales.

The final synthesis map (Fig. 1) shows that bipolar jets emerge from a central core. A deconvolved angular size of about 2 milliarc sec is estimated for the core. The jets extend over 6 milliarc sec on the sky oriented along a position angle (PA) of 125° with respect to the North, and they account for 20% of the total 16 mJy flux density. To obtain some order of magnitude estimates, we will assume that the overall size of the radio source is approximately 6×2 milliarc sec^2. This implies a high brightness temperature of $\sim 9.4 \times 10^7$ K, indicating synchrotron radiation. The LS 5039 radio spectrum as a function of frequency ν, namely $S_\nu \propto \nu^\alpha$, often displays a negative spectral index $\alpha = -0.5$ in agreement with a non-thermal optically thin emission mechanism (*3,4*). The detection of jets occurred at a time when the source was at its typical persistent level of radio emission, and only moderately variable, as inferred from concurrent radio monitoring by the Green Bank Interferometer (GBI) (Fig. 2). The absence of any precursor outburst for the radio jets strongly suggests that they are always present and continuously emanating from the core. The flux density ratio between the SE and NW jet components is estimated as 2.1 ± 0.4. It seems reasonable that this brightness asymmetry reflects a relativistic Doppler boosting effect (*5*). If a continuous jet flow is assumed, the projected velocity required is then $v \cos\theta = (0.15 \pm 0.04)c$, where c is the speed of light and θ the ejection angle with the line of sight. It is straightforward to then derive a lower and upper limit for the jet velocity $[v \geq (0.15 \pm 0.04)c]$ and the ejection angle ($\theta \leq 81^\circ \pm 2^\circ$), respectively.

X-ray binaries with collimated radio jets belong to the class of galactic microquasars. The production of jets is almost certainly related to the capture of matter from a normal star by a black hole or neutron star companion. This is a highly energetic process with observable consequences from radio to hard x-rays (*6*) and possibly beyond. The recent third EGRET catalog of high-energy ($E_\gamma > 100$ MeV) γ-ray sources (*7*) contains nearly 100 unidentified emitters at low galactic latitudes. The position of LS 5039 is well inside the 95% confidence contour of the EGRET source 3EG J1824−1514, whose radius is about 0.5°. Moreover, LS 5039 is the only x-ray emitter within 1° of 3EG J1824−1514 listed in the ROSAT (Roentgen Satellite) All Sky Survey (*8*). Such a good position agreement between an EGRET source and a peculiar radio jet x-ray binary strongly implies that both objects are the same. Thus, this microquasar system is likely associated with an EGRET source. The γ-ray emission observed reveals a rather persistent flux of > 100 MeV photons for the last 10 years (Fig. 3).

Using modern photometric data (*9*) and the reddening free parameter formulation (*10*), we obtained a distance estimate of 3.1 kpc. This value is in excellent agreement with independent results based on the star color excess (*2*). On the other hand, a common intrinsic radio luminosity has been recently suggested for persistent x-ray binaries (*11*). According to this, the LS 5039 average flux density of a few tens of mJy at cm wavelengths would imply a rough distance value not higher than 2 kpc. Thus, different distance indicators show that LS 5039 is nearby, and we adopt a distance of 3 kpc. Therefore, this star appears to be one of the closest, and optically brightest, microquasars among the persistent members of this class. Several other non transient microquasars happen to be beyond distances of about 8 kpc (*12*), such as the prototypical 1E 1740.7−2942 in the heavily obscured regions of the Galactic Center (*13*).

The synchrotron radio luminosity between 0.1 and 100 GHz for this distance is $L_{\rm rad} \sim 7.5 \times 10^{30}$ erg s^{-1}. The average γ-ray flux for all EGRET viewing periods in Fig. 3 is $\Phi_\gamma = (35.2 \pm 6.5) \times 10^{-8}$ photon cm^{-2} s^{-1} with photon spectral index $p = 2.19 \pm 0.18$, where $\Phi_\gamma \propto E_\gamma^{-p}$. The EGRET photon index of LS 5039 is practically identical to that of 1E 1740.7−2942, i.e., steeper than the $p < 2$ values usually found for pulsars (*14*). The corresponding integrated luminosity amounts to $L_\gamma(> 100~{\rm MeV}) \sim 3.8 \times 10^{35}$ erg s^{-1}, compared to an x-ray luminosity (*4*) of $L_X(1.5 - 12~{\rm keV}) \sim 5 \times 10^{34}$ erg s^{-1}. Additional information on the source energetics can be obtained by assuming energy equipartition between the relativistic electrons and the magnetic field (*15*). We are forced to use the overall source parameters observed, because not enough information is yet available for appropriate calculations in the rest frame of the ejecta. The corresponding results are nevertheless expected to be within an order of magnitude for a mildly relativistic system. Under these assumptions, the observed radio properties of LS 5039 imply a total energy content in relativistic electrons of $E_e \sim 4.8 \times 10^{39}$ erg, with an equipartition magnetic field of ~ 0.2 G.

While flowing away into opposite jets, the relativistic electrons are exposed to a huge output of ultraviolet (UV) photons from the hot optical star. Thus, it appears likely that a significant fraction of the EGRET emission arises as a result of inverse Compton (IC) scattering of these photons by the same radio-emitting electrons. The energy shift in this process is such that $E_\gamma \sim \gamma_e^2 E_{\rm ph}$, where the energies of the γ-ray and the stellar photon are related through the squared Lorentz factor of the relativistic electron. For an O7 main sequence star, a UV luminosity of $L_* \sim 10^{38}$ erg s^{-1} is expected to be mostly emitted by photons with $E_{\rm ph} \sim 10$ eV. In order to scatter them into γ-rays with $E_\gamma \sim 100$ MeV, electrons with Lorentz factors $\sim 10^3$, equivalent to energies of $\sim 10^{-3}$ erg, are needed. Considering the persistent EGRET luminosity, the lifetime of such electrons against dominant IC losses will be $t_c \sim E_e/L_\gamma \sim 1.3 \times 10^4$ s.

The electron energy will decay with time by IC scattering according to (*15*) (in centimeter-gram-second units):

$$\left(\frac{dE}{dt}\right)_{\rm IC} = 3.97 \times 10^{-2} U_{\rm rad} E^2 \tag{1}$$

where $U_{\rm rad}$ is the UV radiation energy density. For electrons flowing away into jets, assumed perpendicular to the plane of a circular orbit with radius r, we have $U_{\rm rad} = L_*/4\pi c(r^2 + v^2 t^2)$ at a time t after injection. For an electron with initial energy E_0, its IC lifetime can be expressed as $t_c = 25.2/U_{\rm rad} E_0$ when injected into the jet basis close to the compact object. This implies then that the γ-ray-emitting electrons must be initially exposed to $U_{\rm rad} \sim 2.0$ erg cm^{-3}. Such values of radiation energy density are available if the jets originate at a distance $r \sim 1.2 \times 10^{13}$ cm from the star.

Equation 1 can be solved to give:

$$E(t) = \frac{E_0}{1 + (r/vt_c)\arctan{(vt/r)}}. \tag{2}$$

By imposing the condition that electrons with $E_0 \sim 10^{-3}$ erg are able to abandon the region of heavy IC emission in the star vicinity, the condition $\pi r/2vt_c < 1$ must be fulfilled so that they still retain enough energy to power the extended radio jets. This requirement allows us to constrain the jet velocity to values $v > 0.05c$, in agreement with the previous discussion of Doppler boosting. The true jet velocity is not likely to exceed a mildly relativistic value $v \sim 0.4c$, which we crudely estimate assuming that the 6 milliarc sec extended jets have to be replenished in a t_c time. The Lorentz factor of the jets would then be $\gamma_v = 1/\sqrt{1-(v/c)^2} \sim 1.1$, i.e., not extremely relativistic. The size of the region where γ-rays are produced in this scenario is $vt_c > 1.8 \times 10^{13}$ cm, i.e., larger than the orbital radius.

The central engine in LS 5039 must be supplying $\dot{E}_e \sim L_\gamma \sim 3.8 \times 10^{35}$ erg s^{-1} in the form of relativistic electrons. Their energy distribution is expected to be a power law

$kE^{2\alpha-1}dE = kE^{-2}dE$ to produce the observed spectral index. Assuming electron energies in the range $m_e c^2 \leq \ E \ \leq \gamma_{\rm max} m_e c^2$ we have $\dot{E}_e = k \int E^{2\alpha-1} E dE = k \ln \gamma_{\rm max}$. Therefore, if the proton mass is $m_p \simeq 1800 m_e$ for every relativistic electron, the proton mass flow into the jets can be written as $\dot{M}_{\rm jet} = m_p k \int E^{2\alpha-1} dE \simeq 1800 \dot{E}_e / c^2 \ln \gamma_{\rm max} \sim 1.3 \times 10^{-9}\ M_\odot\ {\rm yr}^{-1}$. The equivalent kinetic luminosity is $L_K = (\gamma_v - 1)\dot{M}_{\rm jet} c^2 \sim 10^{37}$ erg s^{-1}, which is weakly dependent on the maximum energy cutoff assumed ($\gamma_{\rm max} \sim 10^4$). This kinetic power is about four orders of magnitude less than that estimated for the strong ejections of the superluminal microquasar GRS 1915+105 (*16*). Both the mass outflow and kinetic energy estimates would not be significantly affected if positrons are considered instead of protons, because the relativistic mass of an electron with Lorentz factor $\sim 10^3$ is comparable to m_p.

LS 5039 is one of the nearest microquasars to be discovered. It has strong high-energy γ-ray emission, which sets limits on the likely velocity of its jets via inverse Compton energy losses. Most of known microquasars were discovered only after undergoing a noticeable outburst that triggered detection by the battery of satellites and ground-based observatories. Some recent examples include CI Camelopardalis (*17*) and the nearby transient V4641 Sagittarii (*18*). The microquasar nature of these two objects is tantalizing in that both are bright optical stars. CI Camelopardalis was even catalogued as a variable star before its outburst. Therefore, a careful examination of modern archive databases may reveal a previously unnoticed population of microquasars. Indeed, our identification of LS 5039 as a potential candidate resulted from a systematic cross-correlation between public archives of astrophysical data in the x-ray, radio and optical domains (*8, 19, 20*). The success of this approach for systematic identification opens the possibility of new findings which may confirm that the microquasar phenomenon is not as rare as it seems.

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Fig. 1. High-resolution radio map of the nearby star LS 5039 obtained with the VLBA and the VLA in phased array mode at 6 cm wavelength. The presence of radio jets in this high-mass x-ray binary is the main evidence supporting its microquasar nature. The contours shown correspond to 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 40, and 50 times 0.085 mJy beam^{-1}, the rms noise. The ellipse at the bottom right corner represents the half-power beam width of the synthesized beam, 3.4×1.2 (milliarc sec^2) with a PA of 0°. The map is centered at the LS 5039 position $\alpha_{\rm J2000} = 18^h 26^m 15.056^s$ and $\delta_{\rm J2000} = -14°50'54.24''$. North is at the top and East is at the left. One milliarc sec is equivalent to 4.5×10^{13} cm (3 AU) for a distance of 3 kpc.

Fig. 2. GBI radio monitoring of LS 5039, at 2.25 GHz (13 cm), during the weeks before and after the date of our VLBA+VLA observation, indicated by the vertical bar. No strong flaring event was recorded, suggesting that the presence of radio jets must be a permanent feature of LS 5039.

Fig. 3. Radio and γ-ray light curves of LS 5039 and 3EG J1824−1514, which we propose originate in the same object. Both LS 5039 and 3EG J1824−1514 are consistent with a persistent level of emission over the last decade. The fluxes plotted here are taken from the literature and archive data (*3, 4, 19, 21*). Error bars for GBI (±4 mJy) are not shown for clarity, whereas those of the VLA are usually smaller than the symbol size.

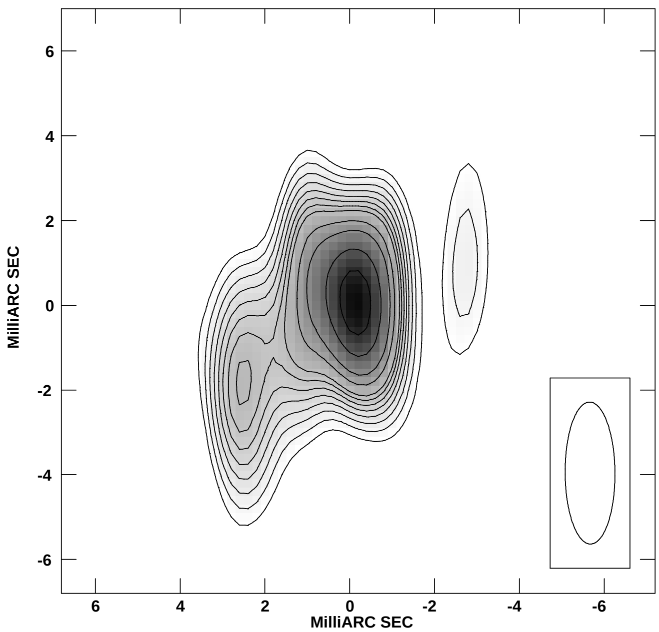

Fig. 1.— J. M. Paredes *et al.*

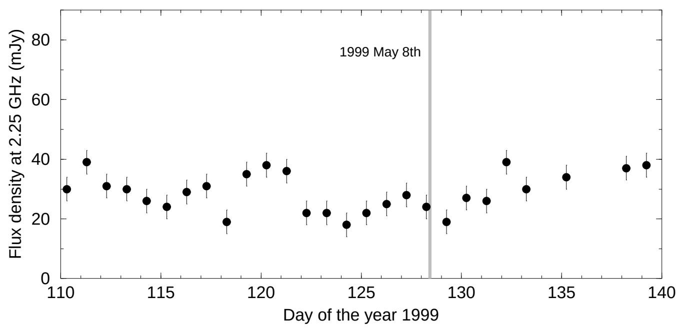

Fig. 2.— J. M. Paredes *et al.*

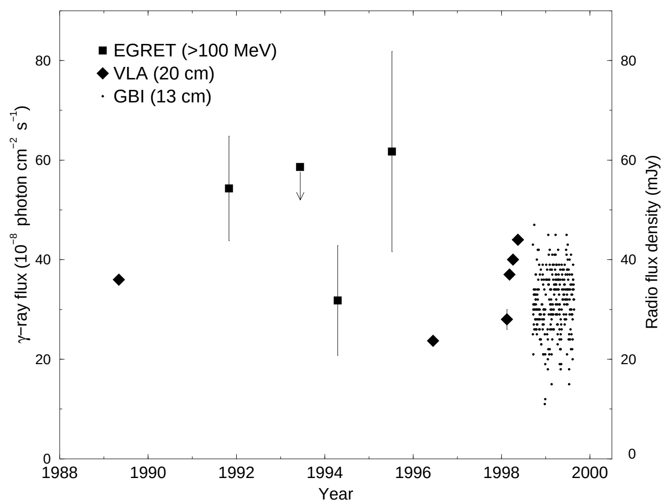

Fig. 3.— J. M. Paredes *et al.*