High energy processes in microquasars

Josep M. Paredes

Departament d’Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, 08028
Barcelona, Spain

Abstract. Microquasars are X-ray binary stars with the capability to generate relativistic jets. It is expected that microquasars are γ-ray sources, because of the analogy with quasars and because the theoretical models predict emission at such energy range. In addition, from observational arguments, there are two microquasars that appear as the possible counterparts for two unidentified high-energy γ-ray sources.

INTRODUCTION

Galactic microquasars are certainly one of the most recent additions to the field of high energy astrophysics and have attracted increasing interest over the last decade. The study of microquasars can contribute to an unified understanding of the accretion and ejection phenomena in the vicinity of collapsed objects ([1]), and can help us explain some of the analogous phenomena observed in distant quasars and active galactic nuclei. They also appear as the possible counterparts for some of the unidentified sources of high-energy gamma-rays detected by the experiment EGRET on board the satellite COMPTON-GRO. However, the γ-ray spectrum of microquasars is the most poorly known, mainly due to the lack of sensitive instrumentation in the past. Thus, microquasars are now primary targets for all of the observatories working in the γ-ray domain. This paper provides a general review of the main observational results obtained up to now as well as a summary of the scenarios for the production of high-energy γ-rays at the present moment.

X-RAY BINARIES AND MICROQUASARS

An X-ray binary is a binary system containing a compact object, either a neutron star or a stellar-mass black hole, that emits X-rays as a result of a process of accretion of matter from the companion star.

In High Mass X-ray Binaries (HMXBs) the donor star is an O or B early type star of mass in the range ∼ 8–20 M⊙ and the typical orbital periods are of several days. HMXBs are conventionally divided into two subgroups: systems containing a B star with emission lines (Be stars), and systems containing a supergiant (SG) O or B star. In the first case, the Be stars do not fill their Roche lobe, and accretion onto the compact object is produced via mass transfer through a decretion disk. Most of these systems are transient X-ray sources during periastron passage. In the second case, OB SG stars,
FIGURE 1. Relativistic radio jets of LS 5039, observed with the VLBA, which reveal its microquasar nature ([22]).

the mass transfer is due to a strong stellar wind and/or to Roche lobe overflow. The X-ray emission is persistent, and large variability is usual. The most recent catalogue of HMXBs was compiled by [2], and contains 130 sources.

In Low Mass X-ray Binaries (LMXBs) the donor has a spectral type later than B, and a mass $\leq 2 \, M_\odot$. Although it is typically a non-degenerated star, there are some examples where the donor is a WD. The orbital periods are in the range 0.2–400 hours, with typical values $< 24$ hours. The orbits are usually circular, and mass transfer is due to Roche lobe overflow. Most of LMXBs are transients, probably as a result of an instability in the accretion disk or a mass ejection episode from the companion. The most recent catalogue of LMXBs was compiled by [3] and contains 150 sources.

The first X-ray binary known to display radio emission was Sco X-1 in the late 1960s. Since then, many X-ray binaries have been detected at radio wavelengths (REXBs). Considering both catalogues together, there are a total of 43 radio emitting sources (8 HMXBs and 35 LMXBs)([4]). Some of these REXBs, those that show a relativistic radio jet, are named microquasars ([1]). In Fig. 1 we show the relativistic jets of the microquasar LS 5039.

The concept of microquasar has been widely accepted in recent years as a new kind of X-ray binary stars in our Galaxy with the capability to generate collimated beams, or jets, of relativistic plasma. The ejection takes place in a bipolar way from the accretion disk associated with the compact star, a black hole or a neutron star. The word microquasar itself was chosen by the analogy of these astronomical objects with quasars and other active galactic nuclei (AGNs) at cosmological distances ([1]). The analogy quasar-
microquasar goes beyond a simple morphological resemblance. Today, there is growing evidence to think that the physics involved in both types of objects is the same, or at least very similar. The key difference would be the distinct order of magnitude of the most significant parameters, especially the mass of the compact object.

The current number of microquasars is $\sim 15$ among the 43 catalogued REXBs (4). Some authors (5; 6) have proposed that all REXBs are microquasars and would be detected as such provided that there is enough sensitivity and/or resolution in the radio observations. The known microquasars, compiled from different sources, are listed in Table 1 where the following information is given: name; type of system; distance; orbital period; mass of the compact object; degree of activity (persistent/transient radio emission); and apparent velocity of the ejecta. Extensive reviews on microquasars can be found in (1), (3) and (7).

MODELS FOR $\gamma$-RAY PRODUCTION IN MICROQUASARS

It is widely accepted that relativistic jets in AGNs are strong emitters of $\gamma$-rays with GeV energies (8). Generally speaking, and allowing for their similarity (11), one could also expect the jets in microquasars to be GeV $\gamma$-ray emitters. In some cases, however, the sensitivity of the current $\gamma$-ray detectors may not be high enough to detect such emission. For instance, based on the physical parameters derived from observations of outbursts, the expected $\gamma$-ray flux of GRS 1915+105 up to very high-energy $\gamma$-rays has been estimated from inverse Compton scattering of the synchrotron photons (9). The resulting fluxes could have been hardly detected by EGRET, being also of transient nature, but they are within the sensitivity of the future AGILE and GLAST missions, about 10–100 times better than that of EGRET.

Several models have been developed to explore the high energy emission from the jets of microquasars. Two kinds of models can be found in the literature depending on whether hadronic or leptonic jet matter dominates the emission at such an energy range: the hadronic jet models (10; 11), and the leptonic jet models. Among leptonic jet models, there are IC jet emission models that can produce X-rays and $\gamma$-rays, based in some cases on the synchrotron self-Compton (SSC) process (i.e. 12; 9), and in other cases on external sources for the IC seed photons (EC) (i.e. 13; 14). In addition, there are synchrotron jet emission models that can produce X-rays (i.e. 15). A general description of such models can be found in (16).

MICROQUASARS AS LOWENERGY $\gamma$-RAY SOURCES

(17) have reported the first high-energy survey catalog obtained with the IBIS $\gamma$-ray imager on board INTEGRAL, covering the first year data. This initial survey has revealed the presence of $\sim 120$ sources detected with a good sensitivity in the energy range 20–100 keV. Among the detected sources, we have inspected the microquasars listed in Table 1 in the second column of Table 2, we list their flux (count/s) and error or upper limit in the energy range of 40–100 keV.
| Name         | System type* | D (kpc) | P<sub>orb</sub> (d) | M<sub>compact</sub> M<sub>☉</sub> | Activity radio† | β<sub> apar</sub> |
|-------------|--------------|---------|----------------------|------------------|-----------------|-----------------|
| **High Mass X-ray Binaries (HMXB)** |              |         |                      |                  |                 |                 |
| LS I +61 303 | B0V          | 2.0     | 26.5                 | −                | p               | ≥ 0.4           |
|            | +NS?         |         |                      |                  |                 |                 |
| V4641 Sgr   | B9III        | ~10     | 2.8                  | 9.6              | t               | ≥ 9.5           |
| LS 5039     | O6.5V((f))   | 2.9     | 4.4                  | 1–3              | p               | ≥ 0.15          |
| SS 433      | evolved A?   | 4.8     | 13.1                 | 11±5?            | p               | 0.26            |
|             | +BH?         |         |                      |                  |                 |                 |
| Cygnus X-1  | O9.7Iab      | 2.5     | 5.6                  | 10.1             | p               |                 |
|             | +BH          |         |                      |                  |                 |                 |
| Cygnus X-3  | WNe          | 9       | 0.2                  | −                | p               | 0.69            |
|             | +BH          |         |                      |                  |                 |                 |
| **Low Mass X-ray Binaries (LMXB)** |              |         |                      |                  |                 |                 |
| Circinus X-1| Subgiant     | 5.5     | 16.6                 | −                | t               | > 15            |
|            | +NS          |         |                      |                  |                 |                 |
| XTE J1550–564| G8–K5V     | 5.3     | 1.5                  | 9.4              | t               | > 2             |
|            | +BH          |         |                      |                  |                 |                 |
| Scorpius X-1| Subgiant     | 2.8     | 0.8                  | 1.4              | p               |                 |
|            | +NS          |         |                      |                  |                 |                 |
| GRO J1655–40| F5Iv        | 3.2     | 2.6                  | 7.02             | t               | 1.1             |
|            | +BH          |         |                      |                  |                 |                 |
| GX 339–4   |              | >6      | 1.76                 | 5.8±0.5          | t               | −               |
|            | +BH          |         |                      |                  |                 |                 |
| 1E 1740.7–2942|          | 8.5?   | 12.5?                | −                | p               | −               |
|            | +BH ?        |         |                      |                  |                 |                 |
| XTE J1748–288|              | ≥8     | ?                    | > 4.5?           | t               | 1.3             |
|            | +BH?         |         |                      |                  |                 |                 |
| GRS 1758–258|              | 8.5?   | 18.5?                | −                | p               | −               |
|            | +BH ?        |         |                      |                  |                 |                 |
| GRS 1915+105| K–M III      | 12.5   | 33.5                 | 14±4             | t               | 1.2–1.7         |
|            | +BH          |         |                      |                  |                 |                 |

* NS: neutron star; BH: black hole
† p: persistent; t: transient

The Burst and Transient Source Experiment (BATSE), aboard the Compton Gamma Ray Observatory (CGRO), monitored the high energy sky using the Earth occultation technique (EOT). A compilation of BATSE EOT observations has been published recently ([18]), with the flux data for the sample being presented in four energy bands. From this catalog we have also selected the data on microquasars. In the third column of Table 2 we have listed their flux in the energy range 160–430 keV in mCrab units. Cygnus X-1 and Cygnus X-3 have been studied extensively by BATSE.

The instrument COMPTEL, also aboard the CGRO, detected 32 steady sources and 31
### TABLE 2. High energy emission from microquasars

| Name            | INTEGRAL* (40–100 keV count/s) | BATSE† (160–430 keV mCrab) | COMPTEL** (1–30 MeV GRO) | EGRET‡ (>100 MeV 3EG) |
|-----------------|---------------------------------|-----------------------------|---------------------------|-----------------------|
| **High Mass X-ray Binaries (HMXB)** |                                 |                             |                           |                       |
| LS I +61 303    | –                               | 5.1±2.1                     | J0241+6119?               | J0241+6103?           |
| V4641 Sgr       | –                               | –                           | –                         | –                     |
| LS 5039         | –                               | 3.7±1.8                     | J1823–12?                 | J1824–1514?           |
| SS 433          | <1.02                           | 0.0±2.8                     | –                         | –                     |
| Cygnus X-1      | 66.4±0.1                        | 924.5±2.5                   | yes                       | –                     |
| Cygnus X-3      | 5.7±0.1                         | 15.5±2.1                    | –                         | –                     |
| **Low Mass X-ray Binaries (LMXB)** |                                 |                             |                           |                       |
| Circinus X-1    | –                               | 0.3±2.6                     | –                         | –                     |
| XTE J1550–564   | 0.6±0.07                        | –2.3±2.5                    | –                         | –                     |
| Scorpius X-1    | 2.3±0.1                         | 9.9±2.2                     | –                         | –                     |
| GRO J1655–40    | –                               | 23.4±3.9                    | –                         | –                     |
| GX 339–4        | 0.55±0.03                       | 580±3.5                     | –                         | –                     |
| 1E 1740.7–2942  | 4.32±0.03                       | 61.2±3.7                    | –                         | –                     |
| XTE J1748–288   | –                               | –                           | –                         | –                     |
| GRS 1758–258    | 3.92±0.03                       | 38.0±3.0                    | –                         | –                     |
| GRS 1915+105    | 8.63±0.13                       | 33.5±2.7                    | –                         | –                     |

* The first IBIS/ISGRI soft gamma-ray galactic plane survey catalog ([17]).
† BATSE Earth occultation catalog, Deep sample results ([18]).
** The first COMPTEL source catalogue ([19]).
‡ The third EGRET catalog of high-energy γ-ray sources ([21]).

γ-ray bursters ([19]). Among the continuum sources detected there are the microquasar Cygnus X-1 and other two sources, GRO J1823–12 and GRO J0241+6119, possibly associated with two other microquasars (see the fourth column in Table 2).

The standard interpretation of the emission in the low-energy γ-ray range is that disc blackbody photons are Comptonized by thermal/nonthermal electrons. There are state transitions (hard and low states) thought to be related to changes in the mass accretion rate. Nevertheless, it is still unclear whether this is what really happens. Alternatively, some groups have suggested that this emission could come from the jet, based on recent observational and theoretical results (see, i.e., [22]; [15]; [14]).

**MICROQUASARS AS HIGH ENERGY γ-RAY SOURCES**

Up to now, there are two HMXB microquasars, LS 5039 and LS I +61 303, that are associated with two EGRET sources. Both sources have been extensively studied at different wavelengths, and both have a very similar spectral energy distribution as can be seen in Figure 2 and Figure 3.
FIGURE 2. Observed spectral energy distribution of LS 5039.

FIGURE 3. Observed spectral energy distribution of LS I +61 303.
The discovery of the microquasar LS 5039, and its possible association with a high-energy $\gamma$-ray source ($E > 100$ MeV), provides observational evidence that microquasars could also be sources of high-energy $\gamma$-rays (22). It is important to point out that this was the first time that an association between a microquasar and a high-energy $\gamma$-ray source was reported. This finding opened up the possibility that other unidentified EGRET sources could also be microquasars. LS 5039 is the only X-ray source from the bright ROSAT catalogue whose position is consistent with the high energy $\gamma$-ray source 3EG J1824−1514. LS 5039 is also the only object simultaneously detected in X-rays and radio which displays bipolar radio jets at sub-arcsecond scales. New observations conducted with the EVN and MERLIN confirm the presence of an asymmetric two-sided jet reaching up to $\sim 1000$ AU on the longest jet arm (23, 4).

Recently, (24) has reported the detection of an unidentified $\gamma$-ray source, GRO J1823−12, at galactic coordinates ($l=17.5^\circ$, $b=-0.5^\circ$) by the COMPTEL experiment. This source is among the strongest COMPTEL sources. The source region, detected at a high significance level, contains several possible counterparts, one of which is LS 5039. It is also worth noting that BATSE has detected this source at soft $\gamma$-rays (see Table 2). Taking into account these observational evidences, from radio to high-energy $\gamma$-rays, LS 5039 appears to be a very likely counterpart of the EGRET source 3EG J1824−1514.

The $\gamma$-ray emission from 3EG J1824−1514, with a luminosity of $L_\gamma(>100$ MeV) $\sim 10^{35}$ erg s$^{-1}$, is likely to originate from inverse Compton effect of the ultraviolet photons from a hot companion star scattered by the same relativistic electrons responsible for the radio emission. The energy shift in this process is given by $E_\gamma \sim \gamma^2 E_{ph}$, where the energies of the $\gamma$-ray and the stellar photon are related by the Lorentz factor of the electrons squared. For an O6.5 star in the main sequence, such as the component of LS 5039, most of its luminosity is radiated by photons with $E_{ph} \sim 10$ eV. In order to scatter them into $\gamma$-ray photons with $E_\gamma \sim 100$ MeV, electrons with a Lorentz factor of $\gamma_e \sim 10^4$, or equivalently with energy $\sim 10^{-2}$ erg, are required.

Recently, (25) have explored with a detailed numerical model if this system can both produce the emission and present the variability detected by EGRET (>100 MeV), and obtained positive results.

After the discovery of relativistic jets in LS I +61 303, this source has been classified as a new microquasar (26, 27). This object has also been proposed to be associated with the $\gamma$-ray source 2CG 135+01 (=3EG J0241+6103) (28; 29). Although the broadband 1 keV–100 MeV spectrum of LS I +61 303 remains uncertain, because OSSE and COMPTEL observations were likely dominated by the quasar QSO 0241+622 emission, the EGRET angular resolution is high enough to exclude this quasar as the source of the high-energy $\gamma$-ray emission (30). BATSE marginally detected the source, and the quasar was also excluded as the origin of this emission (see Table 2). The
The proposed association between LS I +61 303 and the high-energy $\gamma$-ray source is still unclear due to the low angular resolution of EGRET, although no radio loud active galactic nucleus or strong radio pulsar is known within the $\gamma$-ray error box, which includes LS I +61 303 ([29]).

Recently, [31] has carried out a timing analysis of pointed EGRET observations ([32]) suggesting a period of $27.4 \pm 7.2$ days, in agreement with the orbital period of this binary system of 26.496 days. This result, if confirmed, would clearly support the association of LS I +61 303 with 3EG J0241+6103.

This microquasar also seems to be a fast precessing system. MERLIN images obtained in two consecutive days show a change in the direction of the jets of about 50° that has been interpreted as a fast precession of the system ([27]). If this is confirmed, it could solve the puzzling VLBI structures observed so far, as well as the short term variability of the associated $\gamma$-ray source 3EG J0241+6103.

Up to now, the only existing radial velocity curve of LS I +61 303 was that obtained by [33]. Recently, after a spectroscopic campaign, an improved estimation of the orbital parameters has been obtained ([34]). Here, we will just mention the new high eccentricity ($e = 0.72 \pm 0.15$) and the periastron orbital phase at $\sim 0.2$. These values are a key information for any interpretation of the data obtained at any wavelength.

Several models have been proposed to explore the high energy emission of this source (e.g. [35]; [36]; [30]; [37]). The most recent theoretical work has been presented by [38], who explore with a detailed numerical model if this system can both produce the emission and present the variability detected by EGRET (>100 MeV), and obtained positive results.

**High mass microquasars**

Population studies of unidentified EGRET sources suggest that there exists a group formed by young objects distributed along the galactic plane that display clear $\gamma$-ray emission variability on timescales from days to months. [25] have suggested that these sources might be HMXB microquasars and have elaborated some detailed models, that include both external and SSC scattering, to explain the broad-band spectrum all the way up to high-energy $\gamma$-rays. It gives further support to the proposed association between microquasars and $\gamma$-ray sources.

The computed spectral energy distribution of an EGRET source high-mass microquasar is presented in Figure 4. Looking at the Figures 2 and 3, and comparing them with Figure 4, it is seen how the IC jet scenario reproduces pretty well the data, giving further support to the proposal of microquasars as $\gamma$-ray sources.

**MICROQUASARS AS VERY HIGH-ENERGY $\gamma$-RAY SOURCES**

Regarding the physical scenarios where very high-energy $\gamma$-rays could be produced, I expose briefly the general characteristics of hadronic and leptonic jet models. In the context of hadronic jet models, I focus on the work of [10], where the pion-decay emis-
FIGURE 4. Spectral energy distribution model of a high mass microquasar (25).

FIGURE 5. EGRET data points of 3EG J0241+6103 (circles) and the flux upper limits (diamonds) obtained by Whipple (39).
sion produced by interaction between very high energy protons of a jet (100 TeV) and environment cold protons was studied. What is relevant here is the lack of steepening in the energy spectrum of protons, which suffer much less energy losses than electrons, implying a quite hard spectrum of the emission produced by such a mechanism. Therefore, if there is an important population of very high energy protons, significant emission at very high-energy $\gamma$-rays presenting a hard spectrum would be expected. Otherwise, in the context of leptonic jet models, if electrons with energies of the order of TeV are present in the jet, emission up to few hundreds of GeV is predicted (see [9]; [40]). In this case, however, the GeV–TeV spectrum should be quite softer than the one at lower energies, and also softer than the one expected in the hadronic case. The determination of the spectrum of a microquasar at GeV–TeV energies (i.e. photon index, maximum energy, turning point in the slope) would give us information in order to constrain the models of acceleration of particles, jet matter nature, and jet physical conditions in general. These issues will not only improve our knowledge at very high energies, but also in the entire spectrum, going deeper in our knowledge about microquasars.

The observed very high energy (VHE) sky map contains a reduced number of sources. The number of confirmed and probable catalogued sources at present amounts to fourteen (6 AGN, 3 pulsar wind nebulae, 3 supernova remnants, 1 starburst galaxy, and 1 unknown) ([41]). Some microquasars have been observed in the energy range of TeV $\gamma$-rays with the imaging atmospheric Cherenkov telescopes, but none of them has been detected with high confidence yet. Historically, Cygnus X-3 was widely observed with the first generation of TeV instruments. Some groups claimed that they had detected Cygnus X-3 ([42]) whereas other groups failed to detect it ([43]). As the claimed detections have not been confirmed, and the instrumentation at this epoch was limited, these results have not been considered as positive detections by the astronomical community. The HEGRA experiment detected a flux of the order of 0.25 Crab from GRS 1915+105 during the period May-July 1996 when the source was in an active state ([44]). This source has also been observed with Whipple, obtaining a 3.1$\sigma$ significance ([45]). More recently, an upper-limit of 0.35 Crab above 400 GeV has been quoted for GRS 1915+105 ([46]). However, these results need further confirmation given the marginal confidence of the detection. LS 1 +61 303 was observed too, but was not detected in the TeV energy range ([39]). The results, obtained by Whipple at two epochs, show flux upper limits for LS 1 +61 303 (see Figure 5) implying a steepening of the spectrum beyond EGRET energies. The fact that there seems to be a steepening seems to make the leptonic model more likely than the hadronic one.

SUMMARY

The standard physical scenario for microquasars predicts them to be sources of low and high energy $\gamma$-ray emission. Actually, most microquasars have been detected at soft $\gamma$-ray by several instruments on board satellites. At higher energies, microquasars appear as a possible explanation for some of the unidentified high energy $\gamma$-ray sources detected by the experiment EGRET on board the satellite COMPTON-GRO. The possible association between the microquasar LS 5039 and the high-energy $\gamma$-ray source
3EG J1824–1514 provides observational evidence that microquasars could also be sources of high energy $\gamma$-rays \[^{[22]}\]. LS I +61 303 has also been proposed to be associated with the $\gamma$-ray source 2CG 135+01 (=3EG J0241+6103) \(^{[29]}\). Future missions (AGILE, GLAST) will confirm or reject the proposed association between some microquasars and EGRET sources.

From the theoretical point of view, microquasars might emit at hundreds of GeV and beyond. Nevertheless, nearly half of the reduced number of known VHE sources belong to our Galaxy but none of them is a microquasar. The fact that up to now there have not been reliable detections of microquasars, could be more related to the technical development of previous instruments than to the physical capability of microquasars to emit at hundreds of GeV. Observations are not yet conclusive in any way as to whether microquasars emit at such energies. The new generation of Cherenkov imaging telescopes can help clarify this point.

**ACKNOWLEDGMENTS**

I acknowledge partial support by DGI of the Ministerio de Ciencia y Tecnología (Spain) under grant AYA2001-3092, as well as partial support by the European Regional Development Fund (ERDF/FEDER).

**REFERENCES**

1. Mirabel, I.F., Rodríguez, L.F., 1999 ARA&A, 37, 409
2. Liu, Q.Z., van Paradijs, J., van den Heuvel, E.P.J. 2000, A&AS, 147, 25
3. Liu, Q.Z., van Paradijs, J., van den Heuvel, E.P.J. 2001, A&A, 368, 1021
4. Ribó, M., 2002, PhD Thesis, Universitat de Barcelona
5. Fender, R.P. 2001, in "Relativistic flows in Astrophysics", ed. A.W. Guthmann, M. Georganopoulos, K. Manolakou & A. Marcowith, Springer Verlag, Lec. Notes Phys. 589, (2002), 101
6. Fender, R. P. 2004, in 'Compact Stellar X-Ray Sources', eds. W. H. G. Lewin and M. van der Klis, Cambridge University Press, in press \[^{[astro-ph/0303339]}\]
7. Ribó, M. 2004, in ASP Conference Series: "Future Directions in High Resolution Astronomy: A Celebration of the 10th Anniversary of the VLBA", J. D. Romney & M. J. Reid (eds.), \[^{[astro-ph/0402134]}\]
8. von Montigny, C., Bertsch, D.L., Chiang, J., et al., 1995, ApJ, 440, 525
9. Atoyan, A.M., Aharonian, F.A., 1999, MNRAS, 302, 253
10. Romero, G.E. et al., 2003, A&A, 410, L1
11. Bosch-Ramon, V., Aharonian, F.A., Paredes, J.M., 2005, A&A, in press
12. Band, D. L. & Grindlay, J. E. 1986, ApJ, 311, 595
13. Kaufman Bernadó, M. M., Romero, G. E., & Mirabel, I. F. 2002, A&A, 385, L10–L13
14. Georganopoulos, M., Aharonian, F. A., & Kirk, J. G. 2002, A&A, 388, L25
15. Markoff, S., Nowak, M., Corbel, S., Fender, R., & Falcke, H. 2003, A&A, 397, 645
16. Romero G.E., 2004, ChJAA, in press, \[^{[astro-ph/0407461]}\]
17. Bird, A.J., Barlow, E.J., Bassani, L., et al., 2004, ApJ, 607, L33
18. Harmon, B.A., Wilson, C.A., Fishman, G.J., et al., 2004, ApJS, 154, 585
19. Schönfelder, V., Bennett, K., Blom, J.J., et al., 2000, A&AAS, 143, 145
20. Fender, R. P., Gallo, E., & Jonker, P. G. 2003, MNRAS, 343, L99
21. Hartman, R.C., Bertsch, D.L., Bloom, S.D., et al., 1999, ApJS, 123 79
22. Paredes, J.M., Martí, J., Ribó, M., & Massi, M., 2000, Science, 288, 2340
23. Paredes, J.M., Ribó, M., Ros, E., Martí, J., Massi, M., 2002, A&A, 393, L99
24. Collmar, W., 2003, Proc. 4th Agile Science Workshop, Frascati (Rome) on 11-13 June 2003
25. Bosch-Ramon, V., Paredes, J.M., 2004, A&A, 417, 1075
26. Massi, M., Ribó, M., Paredes, J.M., Peracaula, M., Estalella, R., 2001, A&A, 376, 217
27. Massi, M., Ribó, M., Paredes, J.M., Garrington, S.T., Peracaula, M., Martí, J., 2004, A&A, 414, L1
28. Gregory, P. C. & Taylor, A. R. 1978, Nature, 272, 704
29. Kniffen, D.A., Alberts, W.C.K., Bertsch, D.L., et al., 1997, ApJ, 486, 126
30. Harrison, F.A., Ray, P.S., Leahy, D.A., et al., 2000, ApJ, 528, 454
31. Massi, M., 2004, A&A, 422, 267
32. Tavani et al., 1998, ApJ, 497, L89
33. Hutchings, J.B., Crampton, D., 1981, PASP, 93, 486
34. Casares, J., Ribas, I., Paredes, J., Martí, J., Allende Prieto, C., 2004, MNRAS, submitted
35. Taylor, A.R., Young, G., Peracaula, M., et al., 1996, A&A, 305, 817
36. Punslly, B., 1999, ApJ, 519, 336
37. Leahy, D.A., 2004, A&A, 413, 1019
38. Bosch-Ramon, V., Paredes, J.M., 2004, A&A, 425, 1069
39. Hall, T.A., Bond, I.H., Bradbury, S.M., et al., 2003, ApJ, 583, 853
40. Bosch-Ramon, V., Romero, G.E., Paredes, J.M., 2005, A&A, 429, 267
41. Ong, R. E. 2003, in proceedings of ‘The Universe Viewed in Gamma-Rays’, ed. R. Enomoto, Universal Academy Press Inc., Tokyo, in press, [astro-ph/0304336]
42. Chadwick, P.M., Dipper, N.A., Dowthwaite, J.C., et al., 1985, Nature, 318, 642
43. O‘Flaherty, K.S., Cawley, M.F., Fegan, D.J., et al., 1992, ApJ, 396, 674
44. Aharonian, F.A., Heinzelmann, G., 1998, Nucl. Phys. B., 60B, 193
45. Rovero, A.C., Fegan, S., Weekes, T.C., 2002, BAAA, 45, 66
46. Horan, D., Weekes, T., 2003, private communication