Misalignment & Nucleosynthesis in Microquasars†

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We investigate how misalignment and nucleosynthesis in microquasars may be intimately linked. Since the position angles of microquasar orbital planes remain unmeasured, it is quite possible that, in certain cases, the jets lie close enough to their orbital planes so as to periodically impact the companion stars. eg. in V4641Sgr the jet axis is known to lie not more than ~36° from the binary plane (regardless of the orbital plane position angle information). The impact of such a jet on the secondary star will result in the spallogenic nucleosynthesis of the light elements Li, Be & B on the secondary's surface. The integrated yield of such nuclear reactions over the age of the binary system could detectably alter the elemental abundances of the companion star. This scenario could explain the anomalously high Li enhancements (roughly ~20-200 times the sun's photospheric value) seen in the companions of some black-hole X-ray binary systems. (Such enhancements are puzzling since Li nuclei are exceedingly fragile - being easily destroyed in the interiors of stars - and Li would be expected to be depleted rather than enhanced there.) Gamma-ray line signatures of the proposed process could include the 2.22 MeV neutron capture line as well as the 0.478 MeV ^{7}Li* de-excitation line, both of which may be discernable with the *INTEGRAL* satellite if produced in an optically thin region during a large outburst. For very energetic jets, a relatively narrow neutral pion gamma-decay signature at 67.5 MeV could also be measurable with the *GLAST* satellite. We argue that about 10-20% of all microquasar systems ought to be sufficiently misaligned as to be undergoing the proposed jet-secondary impacts.

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† *see Butt, Maccarone & Prantzos, 2003 ApJ, in press for full details*

I. INTRODUCTION

Since the position angles of BHXB orbital planes remain unmeasured, we argue that a significant fraction of microquasar jets could lie close enough to their orbital planes so as to periodically impact the companion stars, and initiate spallative and fusion nuclear reactions thereon. In this way the light-elements Li,Be and B (LiBeB) may be produced *in situ* on the secondary star (see Butt, Maccarone & Prantzos, 2003 for full details). Galaxy-wide, the mass loss from the disks and secondary stars of all such binary systems could serve to disperse significant quantities of freshly synthesized LiBeB into the Interstellar Medium (ISM). There will be an additional contribution to Galactic LiBeB pollution from direct microquasar jet-ISM interactions and we report on this in a forthcoming paper (Butt et al., *in preparation*). The anomalously high Li enhancements – roughly ~20-200 times the sun's photospheric value (Steenbock & Holweger 1984) – seen in the late-type companions of some BHXB systems (Martin et al. 1992, 1996) are very puzzling since Li nuclei are exceedingly fragile, being easily destroyed in the interiors of stars, and so Li would be expected to be depleted rather than enhanced in those stars. We investigate whether jet-secondary interactions could explain such Li overabundances.

II. RELATIVE JET-ORBIT ORIENTATIONS

Theoretical considerations of supernova induced kicks indicate that large spin-orbit misalignments should actually be expected in NS microquasar systems (Brandt & Podsiadlowski, 1995). ie. the distribution of the relative jet axis-orbital plane angles across various microquasar systems ought not to be absolutely random, but that misalignment should be somewhat favored – see Brandt & Podsiadlowski (1995) for why this should be so, and for further discussion.

That the two microquasars where the jet and binary plane inclination angles are somewhat well established (GRO J1655-40 and V4641Sgr) have jets which are not perpendicular to their binary plane (Orosz et al., 2001; Rupen, 2002) suggests that the proposed initial misalignments cannot be too rare. Furthermore, it may be relevant that the accretion disks and jets of 'normal' extragalactic quasars (AGN) have recently been shown to clearly display similar misalignments (Schmitt et al. 2002).

Assuming for simplicity that a jet is directed exactly parallel to the binary plane, one can compute the fraction of the time it will impact the secondary star. In the small angle approximation, the angle subtended by the secondary star will be its diameter divided by the orbital separation: for Roche lobe-filling systems this is given by ~ $0.92(1+q)^{-1/3}$ radians, where $q=M_x/M_2$ is the ratio of the mass of the compact star divided by the mass of the secondary star (Paczynski 1971). The fraction (f_{jet}) of the time the star is intercepting the jet is then simply twice this angle (since there is a jet and a counterjet) divided by the full 2π radians of the orbit. We tabulate f_{jet}, the fraction of time one of the twin persistent jets is being intercepted, under the assumption that the jets lie in the orbital plane, for several system in table 1. A conservative typical value for this duty cycle is ~10 % of the time.

III. Spallative Nucleosynthesis

In order to model the spallative yield on the surface of the secondary star one must know the material composition of both the jet and the surface of the companion, as well as the jet intensity (flux) and speed. Although optical data can tell us about the elemental composition of the secondary companion, the baryonic content of the jet remains largely unknown: models with even purely leptonic jets have been suggested (eg. Kaiser & Hannikainen 2002). Fortunately, in one microquasar system, SS433, high quality X-ray data has provided some insight into the nucleonic content of jets via the detection of red- and blue-shifted X-ray emission lines of Ne, Mg, Si, S, Ar, Ca, Fe and Ni which move in the same ephemeris as the jet precession (eg. Kotani et al. 1994; Marshall, Canizares & Schulz, 2002), suggesting that baryonic jets are certainly not excluded by nature, and may even be the rule rather than the exception, given sufficient measurement sensitivity (eg. Heinz & Sunyaev 2002; see also Distefano et al. 2002).

We deduce a fiducial jet mass transfer rate from the total mass transfer rate given by Brown, Lee & Bethe (2001) of, $\dot{M}_j \sim 5\times10^{-10}$ M⊙ yr^{-1} ~ 2×10^{40} protons s^{-1}, which may be considered a conservative value in view of the jet mass transfer rate of SS433 of $\dot{M}_j$~10^{-7} M⊙ yr^{-1}measured by Marshall, Canizares & Schulz (2002). Since, from the current observational standpoint, the persistent jets of SS433 are possibly the most highly baryonic and most powerful observed, our adopted rate is likely fairly representative for most microquasar systems and sufficiently accurate to at least make a rough assessment of our proposed scenario. At typical BHXB orbital separations of 2-20 R⊙, a jet with ~1^{o} opening angle (eg. Marshall, Canizares & Schulz 2002) yields an irradiated surface of S~10^{17} – 10^{20} cm^2 on the secondary. However, since we are interested in the steady-state *overall* surface LiBeB abundances, and not just the abundances of the exposed section of the secondary, we write the effective beam flux in terms of the jet illuminating the full cross-sectional area of the secondary star, and correcting for the jet impact duty cycle from table 1, we obtain:

$$F_{beam} \sim 8\times10^{16}\,\frac{\dot{m}_{-9}}{R_2 a_{10}}\,protons\ cm^{-2}\sec^{-1} \qquad (1)$$

where $\dot{m}_{-9}$ is the jet mass ejection rate ($\dot{M}_j$) in units of 10^{-9} M⊙/yr. R_2 is the companion radius expressed in $R_\odot$ and a_{10} is the binary separation distance in units of $10R_\odot$. Since most jets are observed to be substantially faster than SS433's (≳0.8c *vs.* 0.26c) we adopt a fiducial value of ~150MeV/n, corresponding to the average value of ~0.5c, as being representative and conservative: the faster the jet, the greater the amount of Li produced. Note that the relevant cross-sections are not very sensitive to the incident particle energy around ~150 MeV/n (MeV per nucleon) – the particle energy affects mainly the ionization range of the jet particles within the surface of the secondary and thus the ‘skin-depth’ of the secondary processed by the jet beam.

Given approximately solar-like initial abundances, the production of Li and other light isotopes occurs via two main channels :

$$\alpha_{jet} + \alpha_{star} \rightarrow {}^{6,7}Li + X$$

$$p_{jet} + (CNO)_{star} \rightarrow {}^{6,7}Li + X$$

the relevant cross-sections, $\sigma_{\alpha-\alpha}$ and $\sigma_{p\text{-}CNO}$, are ~1mbarn and ~10mbarn respectively in the $\gtrsim$100 MeV/n energy range (1 barn=10^{-24} cm^2). These two reactions contribute roughly equally to the production of Li because the product of the number densities $Y_{\alpha\text{-}jet} \times Y_{\alpha\text{-}star}$ is ~10 times greater than the product $Y_{p\text{-}jet} \times Y_{CNO\text{-}star}$ for typical solar system abundances ([H/CNO]~1000 and [He/CNO]~100), which approximately compensates for the lower $\alpha-\alpha$ cross-section. We may then simply multiply the result for the p-CNO Li production rate by a factor of two to arrive at the total Li production rate.

Following the prescription outlined in Butt, Maccarone & Prantzos (2003), we can arrive at the fractional overabundance of Li induced on the surface of the secondary relative to the solar-system value (E_{50} is the particle energy expressed in units of 50 MeV/n):

$$\frac{Y_{Li}}{Y_{Li_\odot}} = \frac{Y_{CNO}}{Y_{Li_\odot}} \frac{10^4 R_2^2 E_{50}^2}{\tau_o} \dot{M}_{tot_{-7}}^{-1} \qquad (2)$$

where τ_o is the the characteristic timescale of Li production and is given by:

$$\tau_o \sim (F\,\sigma)_{\text{total}}^{-1} \sim 10^9 \frac{R_2 a_{10}}{\dot{m}_{-9}} \; sec \qquad (3)$$

(On this timescale, roughly half the CNO and He nuclei exposed to the jet beam are transformed to Li.)

So, for typical values, R_2~1, E_{50}~3, a_{10}~1, $\dot{M}_{tot_{-7}}$~5 & τ_o~10^9sec one should expect a steady state overabundance of Li (with respect to the average solar-system value) on the surface of the companion of a factor of ~8 (or ~2×10^{-5} $Y_{CNO}/Y_{Li_\odot}$), which is greater than but reasonably consistent with the observed values of ($Y_{Li}/Y_{Li_\odot}$)~0.1-1

(Martin et al. 1992, 1996), especially considering that the observed values are, in fact, lower limits due to the ionizing effect of UV and X-ray irradiation (Martin et al. 1996).

It is possible that the enigmatic rapid optical and radio variability of V4641Sgr in radio outburst reported recently (Rupen, Dhawan & Mioduszewski, 2002) could have been the manifestation of an effect induced by the proposed jet-secondary interactions.

A possible observational signature of jet-induced Li production in certain microquasars may be a phase dependence in the strength of optical Li line, although this feature may be quite difficult to discern in practice.

It should be noted that we have (out of necessity) used only rough fiducial input parameters throughout for evaluating the feasibility of our proposed model. Future observational information on jet plasma compositions (ie. the nucleonic fraction) will certainly strongly constrain the nucleosynthetic aspect of our model, and we urge concerted observational efforts in this direction.

IV. THE GAMMA-RAY LINES

Nuclear gamma-ray line features may be expected in the scenario described if they are produced in an optically thin region: the 0.478 MeV line from the deexcitation of ^{7}Li* synthesized in the first excited state; the 2.2 MeV line from neutron capture of neutrons liberated via spallation; the 7.12, 6.92, 6.13, and 2.74 MeV nuclear lines from ^{16}O*; the 4.44 MeV line of ^{12}C*; and, at higher beam energies (E_p>280 MeV), the 67.5 MeV neutral pion-decay "hump" feature may also be present. However, so far no evidence has been found for such lines (eg. SMM, TGRS, COMPTEL & OSSE) except for a possible 2.22 MeV source in COMPTEL data (Harris et al., 1991,1997; McConnell et al. 1997; Harris et al., 2001) and a transient 481± 22 keV feature from BHXB Nova Muscae in ouburst by SIGMA/GRANAT (Goldwurm et al. 1992, Sunyaev et al. 1992). It is plausible that the latter gamma-ray line was, in fact, due to LiBeB nucleosynthesis in jet-secondary interactions, as described here – tellingly, the companion star in Nova Muscae is known to have enhanced Li abundances (Martin et al. 1996).

Observations of gamma-ray line signatures of the proposed process with INTEGRAL will be more sensitive and may prove more fruitful.

Some of the neutrons liberated during the proposed jet-secondary impacts will subsequently capture on the ambient nuclei, via, eg. $n + {}^{1}H \rightarrow {}^{2}H + \gamma_{2.223MeV}$ - there can, however, also be non-radiative neutron capture on ^{3}He to form ^{4}He. If the neutrons are captured deep within the atmosphere of the secondary star then it is likely that the resulting 2.22MeV gamma-ray line will be Compton scattered before emerging from the atmosphere: the mean free path for a 2.22 MeV photon being ~8 g cm^{-2}. A detailed assessment of the neutron capture line intensity and shape, in the context of accretion generated neutrons, can be found in the very comprehensive study of Jean & Guessoum (2001).

VI. DISCUSSION & CONCLUSIONS

We have argued that a significant fraction of galactic microquasar systems' jets may be sufficiently misaligned with respect to their binary planes so as to impact their secondary stars. In this way these jets may play some role in synthesizing the light elements, Li, Be and B *in situ* on the secondary. We have shown that for reasonable values of the parameter space we can reproduce the observed abundances of Li on the surfaces of several such systems. In this preliminary study we have assumed persistent jets throughtout and have neglected any extreme effects due to heating of the secondary star due to the jet power input. [That a microquasar jet may bend (as is seen in some extragalactic jets; eg. Conway & Murphy 1993, Conway & Wrobel, 1995) or that its position angle may be distorted due to relativistic aberration does not impact our hypothesis of possible jet-secondary impacts since the position angles of microquasar orbital planes remain ill-constrained.]

The fact that Li enhancements have been observed in the secondaries of virtually all XBs where they have been searched for – *and, of course, for the stellar types where one expects to be able to discern the optical Li line* – may either imply that jet-disk orientations are not random but that misalignment is the preferred state (eg. Brandt & Podsiadlowski, 1995); or, it may argue for a separate process instead of, or in addition to, the proposed jet-secondary impacts as the source of the observed Li excess. For instance, as proposed by Guessoum & Kazanas (1999), even for well-aligned microquasars (as well as misaligned ones), it is plausible that surface irradiation of the secondary star by neutrons generated in the accretion disk may produce LiBeB via neutron spallation reactions. However such a source is not thought to be a sufficiently prolific producer of Li as to be able to explain the high Li overabundances observed – only in the month or so after a large outburst would such a mechanism be able to explain the observed Li abundances (Guessoum & Kazanas 1999). So such a steady-state process could then perhaps account for a certain minimum level of Li enrichment in XBs with the various possible geometries of jet-secondary impacts explaining the further enhancements and variations in those systems with especially high Li overabundances. Furthermore, it is also possible that in both mis- and well-aligned microquasar systems that Li is generated in the local ISM via jet-ISM interactions (Butt et al., *in preparation*). If sufficient quantities of Li are formed close enough to secondary to be captured by it, this would result in a further steady-state Li enrichment mechanism. However, the statistics of small numbers (six out of fourteen systems listed in Table I have known Li enhancements), together with the unknown distribution of jet-orbital orientations (ie. random *vs.* misalignment favored?), does not yet allow one to draw any firm conclusions about the nature of Li enrichment mechanism.

Analogously to what has been proposed already for AGN's by Famiano et al. (2001), light nuclei will also be synthesized directly in the ISM when microquasar jets impact the ambient media – we discuss this important aspect in a forthcoming paper (Butt et al., *in preparation*). Evidence of such jet-ISM/cloud interactions has, in fact, been already observed in the decelerating jets of XTE J1550-564 (Corbel 2002) and in SS433 (eg. Zealey, Dopita, & Malin, 1980; Fuchs 2002).

Our proposal here is premised on theoretical work (eg. Maccarone 2002; Brandt & Podsiadlowski 1995) which suggests that the jets and orbital planes of microquasars can be far from orthogonal, and for which there is good observational evidence already (Orosz et al., 2001; Rupen 2002; Miller et al., 2002). That normal extragalactic quasars, or AGN, clearly display such jet-disk misalignments (Schmitt et al 2002) may be interpreted as support of our hypothesis.

Direct measurements of the position angles of microquasar binary planes which will allow us to quantitatively assess the nature and statistics of misalignment, however, must await future missions such as the Space Interferometry Mission (Shao, 1998) and MAXIM (Cash, White & Joy, 2001), whose 10^{-5} – 10^{-6} arcsecond angular resolution should be sufficient to separate the various sub-components within individual XBs.

Source	M_x	M_2	q	R_2/a	f_{jet}
V404 Cyg	12±2	0.6	20	0.167	0.11
G2000+25	10±4	0.5	20	0.167	0.11
N Oph 77	6±2	0.3	20	0.167	0.11
N Mus 91	6±2.5	0.8	7.5	0.225	0.14
A0620-00	10±5	0.6	17	0.176	0.11
J0422+32	10±5	0.3	33	0.142	0.09
J1655-40	6.9±1	2.1	3.3	0.284	0.18
4U1543-47	5.0±2.5	2.5	2	0.319	0.20
Cen X-4	1.3±0.6	0.4	3	0.289	0.18
1915+105	14±4	1.2	12	0.198	0.13
V4641Sgr	10.4±1.7	6	1.5	0.340	0.22
QZ Vul	?			0.159	0.10
1550-564	6.9±0.7	1.1	6.6	0.234	0.15
1118+480	6.9	0.5	14	0.2	0.12

Table 1: Using orbital information compiled in the review article by Charles (1998), we tabulate the fraction of the time each microquasar jet impacts its companion star (f_{jet}), under the extreme assumption that the jet lies in the plane of orbit. *a* is the binary separation distance and $q=M_x/M_2$ is the ratio of the mass of the compact star divided by the mass of the secondary star. If R_2 is defined as the equivalent radius of the companion's Roche lobe, then the angle subtended by the secondary star is given by 2 R_2/a ~0.92 $(1+q)^{-1/3}$radians (Paczynski 1971).

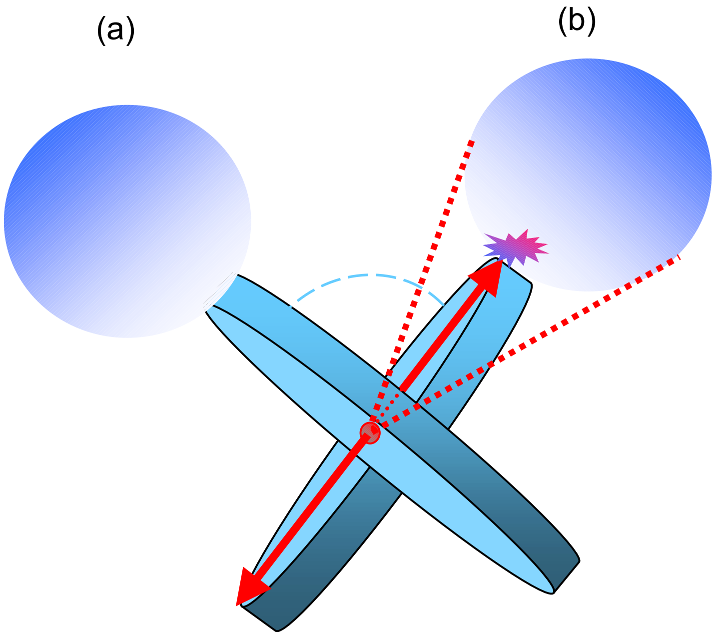

Fig 1: The position angle as well as the inclination angle of a given microquasar jet (thick arrows) can be determined, which fixes its 3D geometry. In contrast, only the inclination angles of binary planes (disks in the schematic above) have thusfar been measured which introduces a degeneracy in the binary plane's possible position angles. Two possible extreme cases are shown above: (a) the "normal" orthogonal assumption; (b) the extreme case of the jet lying in the plane of orbit (shown only for illustration here: it being physically implausible that the jet lies *precisely* in the binary plane without disrupting the accretion disk). In case (b), within the range of relative position angles illustrated by the dotted red lines, the jet will strike the secondary star. Since the jet velocity is typically relativistic, it will initiate nuclear reactions on the secondary star, altering it's chemical content, and producing gamma-rays

REFERENCES

1. Boroson, B., Kallman, T., Vrtilek, S. D., *ApJ*, **562**, 925-935 (2001)
2. Brandt, N. and Podsiadlowski, P., *MNRAS*, **274**, 461-484 (1995)
3. Brown, G. E., Lee, C.-H., Bethe, H., *New Astr.*,**6**, 331-338 (2001)
4. Butt, Y., Maccarone, T. & Prantzos, N., Jet-Induced Nucleosynthesis in Misaligned Microquasars, ApJ, *in press* (2003), astro-ph/0208370
5. Butt, Y, et al., The Microquasar Contribution to Light Element Nucleosynthesis, *in preparation*
6. Cash, W., White, N. & Joy, M., The Maxim Mission: X-ray Interferometry in the New Century in *The New Century of X-ray Astronomy*, ASP Conference Proceedings Vol. 251. Edited by H. Inoue and H. Kunieda. Astronomical Society of the Pacific, p.206 (2001)
7. Charles, P., Black holes in our Galaxy: observations, in *Theory of Black Hole Accretion Disks*, edited by M. A. Abramowicz, G. Bjornsson, and J. E. Pringle. Cambridge University Press, p.1 (1998)
8. Conway, J. E. & Murphy, D. W., *ApJ* **411**, 89 (1993)
9. Conway, J. E. & Wrobel, J. M., *ApJ* **439**, 98 (1995)
10. Corbel, S., Fender, R. P., Tzioumis, A. K., Tomsick, J. A., Orosz, J. A., Miller, J. M., Wijnands, R., Kaaret, P., Science, 298, Issue 5591, pp. 196-199 (2002).
11. Distefano, C. et al., *ApJ*, **575**, 378 (2002)
12. Famiano, M., Vandegriff, J., Boyd, R. N., Kajino, T., Osmer, P., *ApJ*, **547**, L21-L24 (2001)
13. Friend, D. B. and Castor, J. I., *ApJ*, **261**, 293-300 (1982)
14. Fuchs, Y. , Multiwavelength Observation of SS433 Jet Interaction with the Interstellar Medium, To be published in the Conference Proceedings "The Gamma-Ray Universe", XXIInd Moriond Astrophysics Meeting, Les Arcs, Savoie, France, astro-ph/0207429
15. Goldwurm, A., Ballet, J., Cordier, B., Paul, J., Bouchet, L., Roques, J. P., Barret, D., Mandrou, P., Sunyaev, R., Churazov, E., Gilfanov, M., Dyachkov, A., Khavenson, N., Kovtunenko, V., Kremnev, R., Sukhanov, K., *ApJ*, **389L**, 79-82 (1992)
16. Guessoum, N., & Kazanas, D., *ApJ*, **512**, 332-339 (1999)
17. Harris, M., et al., ApJ 381, 439, (1991)
18. Harris, M., et al., in Proc. 4th Compton Symposium, ed. Dermer, Strickalnd & Kurfess, p. 1079 (1997)
19. Harris, M., et al., ApJ 563, 950, (2001)
20. Heinz, S., Sunyaev, R. A., accepted for publication in *A&A*, (2002) astro-ph/0204183

21. Hjellming, R. M., Rupen, M. P., *Nature*, **375**, 464-467 (1995)
22. Jean, P., Guessoum, N., *A&A*, **378**, 509-521 (2001)
23. Kaiser, C. R., Hannikainen, D. C., *MNRAS*, **330**,225-231 (2002)
24. Kotani, T., Kawai, N., Aoki, T., Doty, J., Matsuoka, M., Mitsuda, K., Nagase, F., Ricker, G., White, N. E., *PASJ*, **46L**, 147-150
25. Liping, J., *ApJ*, **356**, 501-506 (1990)
26. Maccarone, T., On the Misalignment of Jets in Microquasars, *MNRAS*, in press (2002)
27. Marshall, H. L., Canizares, C. R., Schulz, N. S., *ApJ*, **564**, 941-952 (2002)
28. Martin, E. L., Casares, J., Charles, P. A., Rebolo, R., *A&A*, **303**, 785-788 (1995)
29. Martin, E. L., Casares, J., Molaro, P., Rebolo, R., Charles, P., *NewAstr.*,**1**,197-205 (1996)
30. Martin, E. L., Rebolo, R., Casares, J., Charles, P. A., *Nature*, **358**,129-131 (1992)
31. McConnell, M. et al., in Proc. 4th Compton Symposium, ed. Dermer, Strickalnd & Kurfess, p. 1099 (1997)
32. Mirabel, I. F., Rodríguez, L. F., *ARA&A*, **37**, 409-443 (1999)
33. Orosz, J. A., Kuulkers, E., van der Klis, M., McClintock, J. E., Garcia, M. R., Callanan, P. J., Bailyn, C. D., Jain, R. K., Remillard, R. A., *ApJ*, **555**, 489-503 (2001)
34. Paczynski, B., *ARA&A*, **9**, 183-208 (1971)
35. Ramaty, R.,Vangioni-Flam, E., Cassé, M., Olive, K., *PASP*, **111**, 651-652 (1999)
36. Romani, R. W., *A&A*, **333**, 583 (1998)
37. Rupen, M., Talk presented at the 4th Microquasar workshop, Cargese, Corsica, France, 2002.
38. Rupen, Dhawan & Mioduszewski, IAU Circ., 7928, 2 (2002).
39. Schmitt, H. R., Pringle, J. E., Clarke, C. J., and Kinney, A. L., **575**, (2002), astro-ph/0204247
40. Shao, M., SIM: the space interferometry mission, *SPIE*, **3350**, 536-540 (1998)
41. Stecker, F. W., *Cosmic Gamma-Rays*, Baltimore: Monograph Book Corp., 1971
42. Steenbock, W., Holweger, H., *A&A*,**130**, 319-323 (1984)
43. Sunyaev, R., Churazov, E., Gilfanov, M., Dyachkov, A., Khavenson, N.,Grebenev, S., Kremnev, R., Sukhanov, K., Goldwurm, A., Ballet, Cordier, B., Paul, J., Denis, M., Vedrenne, G., Niel, M., Jourdain, E., *ApJ*, **389L**, 75-78 (1992)

44. Tavani, M. and London, R., *ApJ*, **410**, 281-294 (1993)

45. Vilhu, O., *A&A*, **388**, 936-939 (2002)

46. Zealey, W. J., Dopita, M. A. & Malin, D. F., *MNRAS* **192**, 731 (1980)

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