Implications of the VHE γ-Ray Spectral Variability of LS 5039

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Abstract. Evidence for orbital modulation of the very high energy (VHE) γ-ray emission from the high-mass X-ray binary and microquasar LS 5039 has recently been reported by the HESS collaboration. The observed flux modulation was found to go in tandem with a change in the GeV – TeV spectral shape, which may partially be a result of $\gamma\gamma$ absorption in the intense radiation field of the massive companion star. In a recent paper [1], I have presented a parameter study of the $\gamma\gamma$ absorption effects in this system. For a range of plausible locations of the VHE γ-ray emission region and the allowable range of viewing angles, the de-absorbed, intrinsic VHE γ-ray spectra and total VHE photon fluxes and luminosities were calculated and compared to luminosity constraints based on Bondi-Hoyle limited wind accretion onto the compact object in LS 5039. It was found that (1) it is impossible to choose the viewing angle and location of the VHE emission region in a way that the intrinsic spectra in superior and inferior conjunction are identical; (2) if the VHE luminosity is limited by wind accretion from the companion star and the system is viewed at an inclination angle of $i > 40^o$, the emission is most likely beamed by a larger Doppler factor than inferred from the dynamics of the large-scale radio outflows; (3) the still poorly constrained viewing angle between the line of sight and the jet axis is most likely substantially smaller than the maximum of $\sim 64^o$ inferred from the lack of eclipses. (4) Consequently, the compact object is more likely to be a black hole rather than a neutron star. (5) There is a limited range of allowed configurations for which the expected VHE neutrino flux would actually anti-correlate with the observed VHE γ-ray emission. If hadronic models for the γ-ray production in LS 5039 apply, a solid detection of the expected VHE neutrino flux and its orbital modulation with km^3 scale water-Cherenkov neutrino detectors might require the accumulation of data over more than 3 years.

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CORRECTING FOR $\gamma\gamma$ ABSORPTION IN LS 5039

LS 5039 is a high-mass X-ray binary in which a compact object is in orbit around an O6.5V type stellar companion. The mass function of the system is $f(M) \approx 5 \times 10^{-3} M_{\odot}$. The binary orbit has an eccentricity of $e = 0.35$, an orbital period of $P = 3.9$ d, a semimajor axis of $a = 2.3 \times 10^{12}$ cm, and the projection of the line of sight onto the orbital plane forms an angle of $\approx 45^o$ with the semimajor axis [3]. The inclination angle i is only poorly constrained in the range $13^o < i < 64^o$, and has been left as a free paprameter. EVN and MERLIN observations of the radio jets of LS 5039 suggest a mildly relativistic flow speed of $\beta \sim 0.2$ (corresponding to $\Gamma = 1.02$) on the length scale of several hundred AU [5]. However, it is plausible to assume that near the base of the jet, where the VHE γ-ray emission may arise, the flow may have a substantially higher speed. Therefore, bulk flow speeds of $\Gamma \sim 2$, more typical of the jet speeds of other Galactic microquasar jets, were also considered. In [1], the observed VHE γ-ray spectra in inferior and superior conjunction of LS 5039 have been corrected for $\gamma\gamma$ absorption, using the prescription of [2]. A parameter study has been carried out, investigating a plausible range of heights of the emission region above the compact object and inclination angles $i = 20^o$, 40^o, and 60^o. Based on inferred integrated VHE fluxes (and thus inferred, apparent isotropic luminosities), important constraints on the intrinsic VHE γ-ray emission and the energetics of the system could be inferred. Fig. 2 summarizes the resulting constraints for a configuration with a bulk Lorentz factor $\Gamma = 2$ of the emitting region.

SUMMARY OF RESULTS

- It is impossible to choose the viewing angle and location of the VHE emission region in a way that the intrinsic (deabsorbed) fluxes and spectra in superior and inferior conjunction are identical. Consequently, the intrinsic VHE luminosities and spectral shapes must be fundamentally different in different orbital phases.

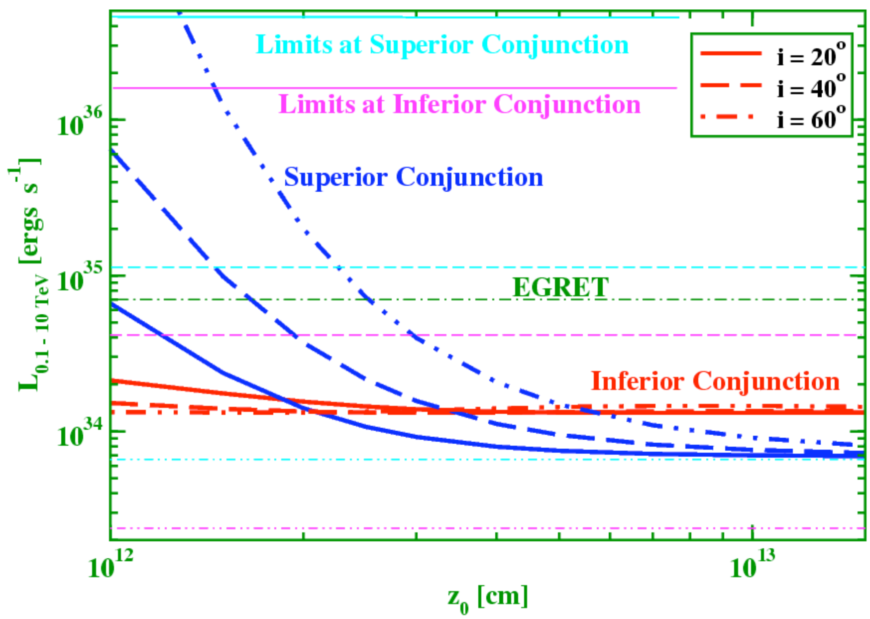

FIGURE 1. Inferred apparent isotropic luminosities for LS 5039 (thick curves), compared to the luminosity limits from Bondi-Hoyle limited wind accretion (horizontal lines), assuming Doppler boosting of the emission corresponding to $\Gamma = 2$. Allowed configurations are those for which the inferred luminosities are substantially below the respective luminosity limits.

- It was found that the luminosity constraints for an inclination angle of $i = 60^o$ at inferior conjunction could not be satisfied at all, and for $i = 40^o$, there is no allowed configuration in agreement with the luminosity constraint for $\Gamma = 1.02$. From this, it may be concluded that, if the VHE luminosity is limited by wind accretion from the companion star and the system is viewed at an inclination angle of $i > 40^o$, the emission is most likely beamed by a larger Doppler factor than 1.02 as inferred from the dynamics of the large-scale radio outflows on scales of several hundred AU.
- Since it was found to be impossible to satisfy the luminosity constraint for inferior conjunction at a viewing angle of $i = 60^o$, one can constrain the viewing angle to values substantially smaller than the maximum of $\sim 64^o$ inferred from the lack of eclipses.
- The previous two points as well as the fact that the luminosity limits can easily be satisfied for $i = 20^o$, indicate that a rather small inclination angle $i \sim 20^o$ may be preferred. Thus, the compact object might be a black hole rather than a neutron star.
- Under the assumption of a photon-to-neutrino ratio of ~ 1 (before $\gamma\gamma$ absorption), the detection of the neutrino flux from LS 5039 and its orbital modulation might require the accumulation of data over more than 3 years with km^3 scale neutrino detectors like ANTARES, NEMO, or KM3Net.
- There is a limited range of allowed configurations for which the expected VHE neutrino flux would actually anti-correlate with the observed VHE γ-ray emission. Thus, strategies for the identification of high-energy neutrinos from microquasars based on a positive correlation with observed VHE fluxes may fail if models with $z_0 < 2.5 \times 10^{12}$ cm apply.

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