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https://doi.org/10.3390/particles7030047 *particles*

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W 50 Morphology and the Dynamics of SS 433 Formation—The Origin of TeV Gammas from the Microquasar

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Abstract: The precessing jets of microquasar SS 433 have punched through the supernova remnant W 50 from the explosion forming the compact object. The jets collimate before reaching beyond the shell, some 40 pc downstream, just the region of origin of TeV gamma radiation. Collimation could be effected by ambient pressure in the SNR cavity; I investigate conditions under which the W 50 morphology and the sites of TeV gamma radiation can be explained in terms of collimation, with associated shocks, induced by ambient pressure. The SNR is now ~10^5 years after the supernova; with the present pressure, collimation and associated shocks would indeed occur ~40 pc downstream. Modeling of the evolution of binary systems indicates that the Roche lobe overflow and the initiation of the jets may be recent rather than early; present day collimation would still occur ~40 pc downstream, but the cone angle of the precession must then have increased with time—driven by the Roche lobe overflow. The morphology of W 50 and the site of the origin of TeV radiation are readily explained in terms of the collimation of the jets by internal SNR pressure.

Keywords: stars; binaries; SS 433; circumstellar matter; W 50; TeV gamma astronomy

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Citation: Bowler, M. W 50 Morphology and the Dynamics of SS 433 Formation—The Origin of TeV Gammas from the Microquasar. *Particles* **2024**, *7*, 805–809. https://doi.org/10.3390/particles7030047

Academic Editor: Theocharis Kosmas

Received: 13 August 2024
Revised: 29 August 2024
Accepted: 2 September 2024
Published: 4 September 2024

1. Introduction

The Galactic microquasar SS 433 is distinguished by jets observed from radio wavelengths through the optical spectrum to soft X-rays. These opposite jets, at a speed of 0.26 c, define an axis that precesses about the normal to the orbital plane of this binary system, with a period of approximately 162 days, tracing out a cone. These jets are themselves unusual; the optical spectra are strong in the emission lines of both Balmer H_α and He I. Thus, the jets are baryon-loaded and believed to be accelerated from the core of a thick accretion disk, probably by radiation pressure in some form. Reviews may be found in [1,2]. The microquasar sits in the middle of the nebula W 50 and this nebula has a peculiar morphology. It has the appearance of a spherical shell, of radius ~45 pc, through which two lobes or ears, east and west, have been extended, aligned with the precession axis of the jets. These lobes appear in radio and X-ray images about 50 pc from the central engine and reach over 100 pc to the east, rather less to the west (Figure 1). The precessing jets themselves have not been tracked beyond ~10^{-1} pc, in radio. The curious morphology of W 50 and the alignment of the lobes with the precession axis of the jets has for a very long time been interpreted as an approximately spherical supernova remnant pierced by the kinematic jets of SS 433. The recent observation of TeV gammas from the regions just before the jets supposedly pierce the shell is particularly convincing, [3] HAWC and [4] HESS. The lobes do not expand with distance as might be expected; the precessing jets must have been collimated as approximately cylindrical jets before extruding through the remnant shell. Alternatively, there might be at least two episodes with different precession angles or a steady increase in precession angle from early on to the present day. Either is capable of getting the morphology of W 50 more or less right [5,6].

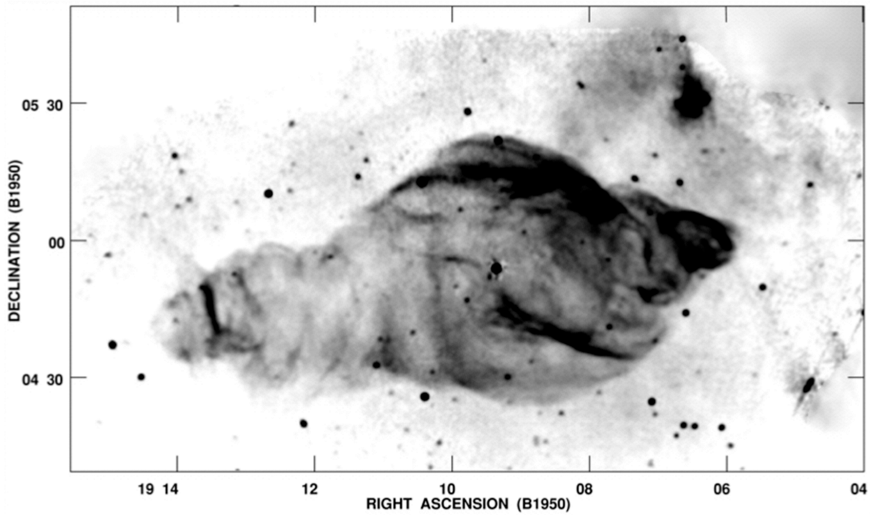

Figure 1. An aide memoire: the famous radio image of the nebula W 50 from Dubner et al. (1998) [7]. East is to the left and the tips of the lobes are separated by ~200 pc.

2. Collimation

A scenario with active collimation was devised following numerical work propagating realistic jets through an unrealistic ambient medium [8], unrealistic in the sense that the density and temperature of the medium into which the jets are expanding were chosen to be much higher than would exist in the SNR cavity. Yet the choice of medium in [8] was serendipitous, because it revealed features that would have likely remained obscure with a more realistic medium. In the numerical calculations of [8], precessing jets with SS 433 characteristics undergo an abrupt change in morphology, as a result of the ambient pressure. They become (hollow) cylindrical jets encased within a cocoon, as shown in Figure 2, with the head of the cylindrical jet propagating much slower than the launch speed of the precessing jets. The specific results of [8] can be scaled, for a given geometry, with various values of the ambient temperature and pressure [9]. For an ambient pressure P, (which squeezes the precession cone) and ambient density ρ, the distance between the jet origin and the change in morphology scales as $1/\sqrt{P}$. The head advances at a speed close to the speed of sound in the ambient medium in the region where the morphology changes, scaling with $\sqrt{P/\rho}$, that is, with the square root of the temperature [9]. These scaling relations and their origins are discussed in considerable detail in [9]. The jets are presumably launched within an already expanding supernova cavity. Using a particular SNR model [10] for the evolution of ambient pressure and temperature within the cavity, I found that, if launched early, within ~10^4 years of the supernova explosion, the morphology initially changes after ~9 pc, at a temperature of ~10^8 K, and thereafter the head advances at ~0.003 c [9]. At this speed, it would take ~10^5 years to cover 100 pc, and that is about the age of the expanding supernova remnant.

However, the jets are launching when ~10^5 years have passed. The morphology is changing ~40 pc downstream (still inside the cavity) and at a temperature of ~10^6 K. The collimated jet would take a further ~10^5 years to cover a further 10 pc, but the lobes extend a further 50 pc or so beyond the remnant shell. It is therefore natural to suppose that the supernova exploded ~10^5 years ago and that the jets started up within ~10^4 years of the explosion and kept going. This is the scenario in [9].

Using the model [10] of the expanding SNR, I find that it takes about 8×10^4 years to reach the present radius of 45 pc. At this time, the ambient pressure within the SNR has dropped to $10^{-10.5}$ erg cm^{-3} [10] and collimation takes place 35 pc downstream; this result does not depend on when the jets started up. The observed TeV gammas originate from ~30–40 pc downstream (HAWC and HESS); collimation shocks due to ambient pressure in the expanded SNR cavity would occur today ~35 pc downstream. The HESS data are particularly useful because the angular resolution is sufficient to distinguish between the origin of three groups of energy, with gammas over 10 TeV being the best indicator of the shock location, and this is indeed ~35 pc downstream [4]. This is almost sufficient to establish the potential for collimation by ambient pressure to explain the source of TeV gammas, but the morphology of W 50 depends on the origin of the lobes and this in turn depends on whether they started up early or late. There are reasons to suppose that the jets have started up recently, ~10^5 years after the supernova explosion, based on modelling the evolution of binaries destined to end up like SS 433 [11]. These calculations proffer independent support for the model SNR cavity.

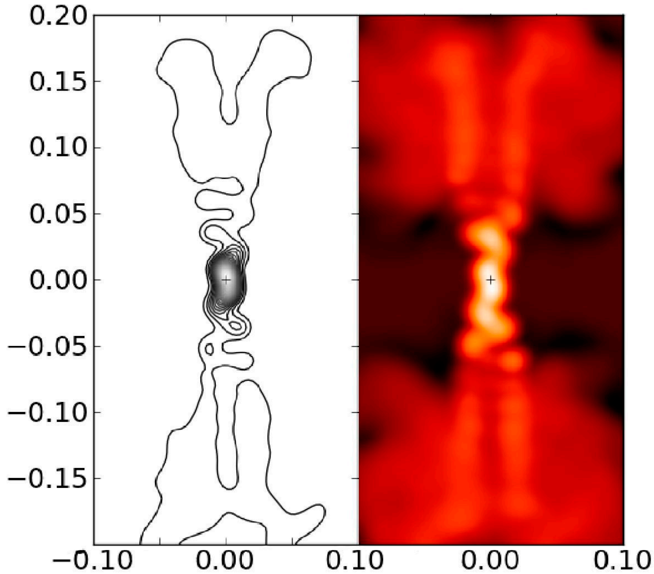

Figure 2. Two renderings of the slowing down and collimation of SS 433 jets in an unrealistically dense and hot environment. The units are pc; thus, the precessing jets are collimated into hollow cylinders at 0.07 pc from the source of the jets. From [8,9], for completeness.

3. Evolution of Binaries Destined to Look Like SS 433

A paper by Han and Li (2020) [11] presents an ambitious set of calculations on the formation of the binary system SS 433. Binaries consisting of zero-age main sequence stars were evolved both dynamically and through stellar evolution. Some examples ended up similar to SS 433 with a black hole, a massive companion and an orbital period of about 13 days. Han and Li [11] present as an example a system containing a black hole of mass ~8 $M_\odot$ and a companion of mass ~24 $M_\odot$. Roche lobe overflow commenced within 10^4 years of the explosion and a period of about 13 days was reached after about 5×10^4 years, much as was proposed in [9]. [This example is not a good model for SS 433; if the mass ratio were 0.3, then, using the period and orbital speed of the compact object, the masses come out as ~4 and 12 $M_\odot$.] Having reason to think that the mass ratio in SS 433 is ~0.7 rather than ~0.3, corresponding to masses of ~15 and 21 $M_\odot$ [12], I was interested in details of any examples ending up with such masses and an orbital period of about 13 days. Li very kindly provided me with a list of properties of 16 examples close to these conditions. The times between the explosion and the overflow of the Roche lobe were ~8×10^4 years, in remarkable agreement with the time taken for the model SNR to expand to 45 pc, with the overflow then being sustained for about 10^4 years. Such late jets would collimate ~35 pc downstream, close to where HESS finds the source of >10 TeV gammas. This would seem satisfactory but there remains a problem in understanding the morphology of W 50. If the jets had always been as they are today, but for a mere 10^4 years, they would have collimated within the remnant shell but could never have produced the lobes extending to 120 pc to the east and 85 pc to the west; the speed of advance of the heads of the cylindrical jets would be far too low. I therefore investigated what conditions might allow both the long wait (latency [6]) of ~8×10^4 years (the time taken for the companion to fill its Roche lobe) and the extension of the lobes far beyond the supernova remnant.

3.1. The Need for Something Else

With these timescales, the lobes would have had to be produced by something other than the current jet configuration. Today's disk follows the spin axis of the companion; the normal to the disk orients parallel to that axis, [13] and earlier references therein; the latest piece of evidence can be found in [14]. That the lobes extrude along the precession axis of today's jets implies that the jets first collimated must have propagated with much greater head speeds, presumably in the early stages of Roche lobe overflow. Suppose that the precession cone angle shifted continuously from an initial small value to the present day of θ ~ 20°, not necessarily in a linear fashion. For a small value of the angle θ, the collimation distance shrinks as ~$sin\ \theta$ (Equation (2b) of [9]) and the speed of advance of the head of the collimated jet increases as ~$1/sin\theta tan\theta$ (Equation (4) of [9]); the head does not exceed the speed of the transport of matter within the jet as θ goes to 0. If the spin axis of the companion misaligned progressively with the orbital angular momentum vector, the morphology of the nebula W 50 can be accounted for in terms of recently initiated jets of SS 433, an alternative to the early jet scenario.

3.2. Roche Lobe Overflow and Spin Migration

The possibility of accounting for the morphology of W 50 in terms of 3.1 was investigated in [5,6], with no attention to any mechanism that might migrate the spin of the massive companion star. There is, however, a mechanism: the transfer of matter from the companion via Roche lobe overflow through the L_1 point misaligns the spin of the companion [15]. It is, of course, just such a transfer that maintains the accretion disk of SS 433, sustaining the jets and the wind from the disk. Sufficiently high rates of mass transfer from the companion can overcome tidal effects; the rate of change in the angle θ grows with the rate of mass transfer (Equation (50) of [15]). The present day rate of mass transfer is high, ~$10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ [16,17], and in the models of [11], there are (brief) periods of rates as high as $10^{-3}\ M_{\odot}\ \mathrm{yr}^{-1}$. In this emerging picture, the jets are initialized when the Roche lobe overflow commences, with a small angle θ. Collimation is accomplished a short way downstream and the dense cylindrical jet propagates rapidly, punching through the remnant and producing the extended lobes. As time goes on, the precession angle θ increases, the jets collimate further downstream, the cylindrical cross section grows and the head propagates slower, possibly blending the lobes into the supernova remnant shell.

4. Conclusions

The authors of the HESS paper discounted the action of ambient pressure on the collimation of the jets, arguing that would effect collimation much too close to the binary. This is true for jet production in a young SNR, but not for Roche overflow and jet production after the SNR has already expanded substantially. I conclude that collimation shock today is expected to occur a little less than 40 pc downstream. There is a plausible natural explanation for both the morphology of W 50 and the location of origin of the gamma rays of energy >10 TeV, namely the collimation of the precessing jets by the ambient pressure within the supernova cavity. If the latency period of SS 433 is as great as ~10^5 years, as in the evolutionary models of Han and Li [11], coupling with the drift of the precession cone angle θ during Roche lobe overflow would seem sufficient to match the topology.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Acknowledgments: I thank Xiang-Dong Li for making available to me summaries of the results of calculations of the evolution of rather massive binaries and for his prompt responses to my subsequent queries.

Conflicts of Interest: The author declares no conflicts of interest.

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