# PRECESSING JET MODEL FOR THE SUPERNOVA REMNANT G109.1-1.0

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We propose that the central X-ray pulsar in G109.1-1.0, designated 1E 2259+586, ejects two oppositely directed precessing jets or beams, which give rise to the observed radio structure. The radio emission is interpreted as synchrotron emission from electrons accelerated at the interface of the jets with the walls of the SNR. Thus the observed intersecting arcs of radio emission represent the trace of the precessing jets on the supernova remnant walls. The precession axis is inclined at 37 degrees to the line of sight and the precession cone half angle is 55 degrees. The observed large scale X-ray jet in G109.1-1.0 is found to coincide in position with the precession axis as was found for the X-ray jets from SS 433.

## INTRODUCTION

The extraordinary supernova remnant G109.1-1.0 has been under intensive study since its discovery in 1980 (Gregory & Fahlman, 1980; Hughes, Harten & Van den Bergh, 1981). It is remarkable because of the presence of an X-ray pulsar (Fahlman & Gregory, 1981 & 1983) at the center of curvature of the semi-circular shaped remnant and because of a jet like feature emerging from the pulsar on the eastern side. A detailed comparison of the X-ray and radio morphology of the supernova remnant (SNR) and the relationship of the remnant to the neighbouring molecular cloud has been presented by Gregory et al. (1983). Although the overall extent of the radio and X-ray emission is similar, in detail the distributions are very different (see figures 3 & 4) with the radio emission resembling two intersecting arcs. There is also clear evidence to suggest that the supernova is interacting with a molecular cloud on the western side (Gregory et al., 1983; Heydari-Malayeri et al., 1981). In overall morphology the SNR resembles a hemisphere. In this paper, we interpret the radio structure in terms of a simple kinematic precessing jet model as first proposed by Gregory and Fahlman in 1980. In this model, the radio emission is synchroton radiation from relativistic electrons accelerated in the interaction of the twin precessing jets with



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the walls of the SNR. We do not consider here the details of this interaction or the nature and generation of the jets themselves.

## PRECESSING JET MODEL

Figure 1(a) shows a sketch of the proposed jet model for a perfectly spherical SNR cavity. The precessing jets lie along the surfaces of two

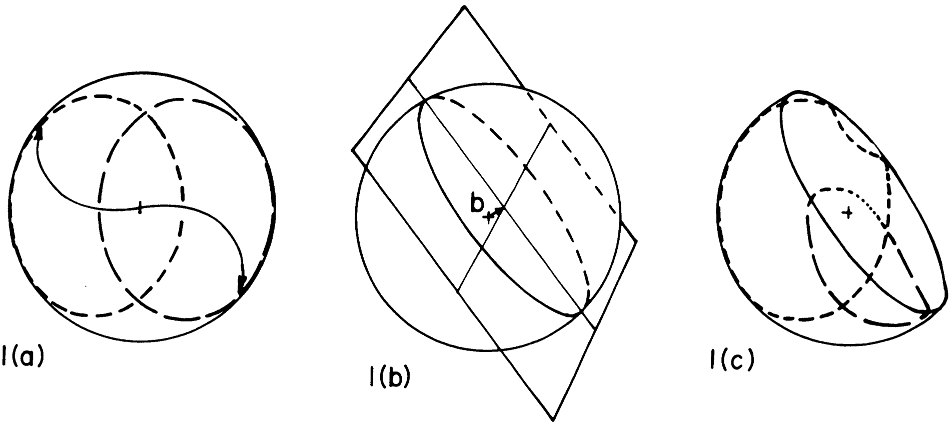


Figure 1. The precessing jet model for a perfectly spherical SNR is shown in 1(a). The dashed ellipses are the traces of the two jets on the walls of the SNR. The interaction with the molecular cloud is represented by the intersecting plane in 1(b). The traces of the two jets on the resulting SNR cavity appear in 1(c).

cones which intersect the spherical cavity in two circles. For a precession cone half angle of 55 degrees and precession axis inclined at 37 degrees to the line of sight the two circular traces appear as intersecting ellipses as shown by the dashed lines. Because of the interaction with the neighbouring molecular cloud, the SNR cavity resembles a hemisphere. For the purpose of this analysis, we have modelled the interaction with the molecular cloud by a plane which cuts off a portion of the spherical cavity as shown in figure 1(b). This interface causes the trace of the jets to depart from perfect ellipses (figure 1(c)).

The coordinate system employed for this kinematic model is shown in figure 2. The pulsar which is assumed to be the source of the two precessing jets is at rest at the origin of the right-handed coordinate system $x'$, $y'$, $z'$. The $y'$ axis is in the sky plane, and $z'$ is the axis about which the jets precess with an angular velocity $\Omega$ and at an angle $\psi$. Consider a second right-handed coordinate system $x$, $y$, $z$ which is formed by rotating the $x'$, $y'$, $z'$ axes about the $y'$ axis until the $z$ axis

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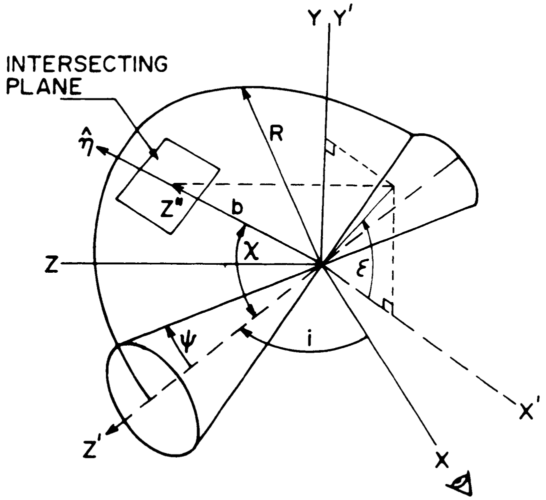


Figure 2. The coordinate system used to discuss the geometry of the kinematic model.

is in the sky plane and the x axis coincides with the line of sight to the observer. The precession axis z' lies in the x-z plane and is inclined to the line of sight by the angle i. We use a third coordinate system x", y", z" to describe the orientation of the intersecting plane representing the molecular cloud interface. The z" axis is parallel to the $\hat{\eta}$ unit vector which denotes the normal to the plane and b is the distance of the plane from the pulsar in units of R, the radius of the spherical portion of the SNR cavity. The x", y", z" axes are formed by rotating the x', y', z' axes about the z' axis through an angle $\varepsilon$ followed by a rotation of $\chi$ about the new y" axis. Thus the interaction plane is specified with respect to the x', y', z' axes by the coordinates b, $\varepsilon$, $\chi$.

Let $\underset{\sim}{r}$ represent the instantaneous point of intersection of either jet with the walls of the SNR. The vector $\underset{\sim}{r}$ can be specified in terms of spherical polar coordinates with $\psi$ as the polar angle with respect to the z' axis, $\theta$, the azimuthal angle measured in the x'-y' plane and r, the distance to the wall of the SNR in that direction. The projection of $\underset{\sim}{r}$ on to the sky plane (y, z plane) is given by the following components.

$$\underset{\sim}{r} \cdot \hat{y} = s_{jet}\, r \sin \psi \sin \theta \qquad (1)$$

and

$$\underset{\sim}{r} \cdot \hat{z} = s_{jet}\, r\{\sin i \cos \psi - \cos i \sin \psi \cos \theta\} \qquad (2)$$

where $s_{jet}$ is a sign parameter equal to +1 for the jet moving mostly towards the observer and -1 for the counter jet. For a spherical SNR cavity, the parameters i, $\psi$ and R are given by:

$$2 \cos i = \frac{(\underset{\sim}{r} \cdot \hat{z})\max - (\underset{\sim}{r} \cdot \hat{z}) \min}{(\underset{\sim}{r} \cdot \hat{y})\max} \tag{3}$$

$$2 \sin i \cot \psi = \frac{(\underset{\sim}{r} \cdot \hat{z})\max + (\underset{\sim}{r} \cdot \hat{z})\min}{(\underset{\sim}{r} \cdot \hat{y})\max} \tag{4}$$

$$R \sin \psi = (\underset{\sim}{r} \cdot \hat{y})\max \tag{5}$$

In the case of a spherical cavity intersected by a plane, the value of r will vary with the beam direction and depend on the angle $\phi$ between $\hat{\eta}$, the normal to the plane, and $\underset{\sim}{r}$. The angle $\phi$ is given by

$$\cos \phi = \hat{\eta} \cdot \underset{\sim}{r} = \sin \chi \cos \varepsilon \sin \psi \cos \theta + \sin \chi \sin \varepsilon \sin \psi \sin \theta + \cos \chi \cos \psi \tag{6}$$

If $\phi \geq \cos^{-1}$ (b) then r = R.

If $\phi < \cos^{-1}$ (b) then b R sec $\phi$.

For a particular choice of parameters i, $\psi$, b, $\chi$ and $\varepsilon$, equations 1, 2 & 6 describe the trace of the two beams on the walls of the SNR cavity as projected onto the sky plane.

To compare the model with observations, in particular CO observations of the molecular cloud, we also require equations describing the locus of intersection of the plane and spherical cavity projected on to the sky plane. If we let $\underset{\sim}{q}$ be the locus of this intersection, then the y and z components of $\underset{\sim}{q}$ are given by:

$$\underset{\sim}{q} \cdot \hat{y} = R[\sin \phi_o \cos A \sin \varepsilon \cos \chi + \sin \phi_o \sin A \cos \varepsilon + \cos \phi_o \sin \varepsilon \sin \chi] \tag{7}$$

$$\underset{\sim}{q} \cdot \hat{z} = R[\sin \phi_o \{\cos A(-\sin i \sin \chi - \cos \varepsilon \cos i \cos \chi) + \sin \varepsilon \sin A \cos i\} + \cos \phi_o(\sin i \cos \chi - \cos i \cos \varepsilon \sin \chi)] \tag{8}$$

where $\phi_o = \cos^{-1}$ (b). The locus is then obtained by varying the parameter A from $0 \rightarrow 2\pi$.

The model described above has been fit to the 20 cm VLA radio observations of Gregory et al. (1983). Equations 3, 4, & 5 were used to determine i, $\psi$ and R and the remaining parameters b, $\chi$ and $\varepsilon$ found from trial model calculations. Figure 1 (c) shows the best fitting model and figure 3 shows this model superposed on the 20 cm radio contours. The jet traces are shown as dashed lines and the SNR walls are the solid

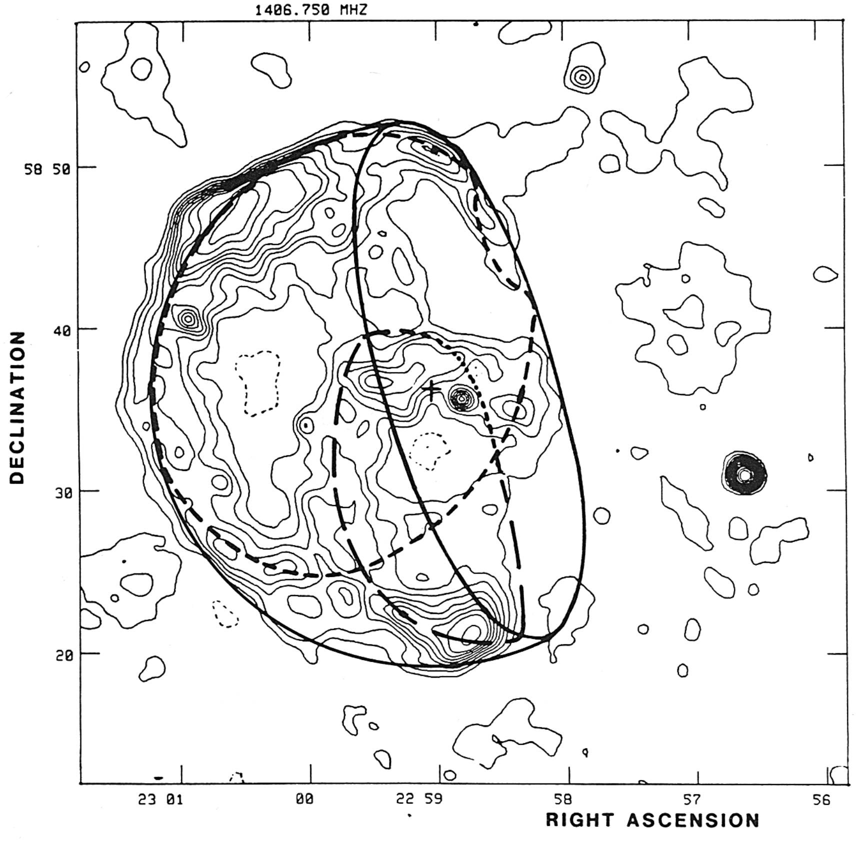


Figure 3. The precessing jet model superposed on our 20 cm VLA radio map. The dashed curves are the traces of theprecessing jets on the walls of the SNR. The solid curves indicate the boundaries of the SNR cavity. The cross indicates the location of the pulsar.

lines. The same model fit is obtained for two sets of model parameters depending on which jet is assumed to be towards the observer.

$$i = \begin{pmatrix} -37 \\ +37 \end{pmatrix} \pm 3, \quad \psi = 55° \pm 5, \quad b = 0.15 \pm .05,$$

$$\chi = \begin{pmatrix} 45 \\ 135 \end{pmatrix} \pm 5, \quad \varepsilon = 55° \pm 5 \text{ and } R = 16.6 \pm 0.5 \text{ arcmin}.$$

Where two values are quoted the upper value corresponds to the western jet towards the observer. For the western jet toward the observer, the

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orientation of the molecular cloud interaction plane is such that the eastern most extension of the cloud would give rise to a wedge like absorption screen over the western portion of the SNR.

From the model parameters derived from the fit to the radio data, we can deduce the orientation of the precession axis of the jets. The jet model and precession axis, indicated by the arrow, are superposed on the X-ray contours in figure 4. We note that the X-ray jet lies along the direction of the precession axis derived from the radio structure.

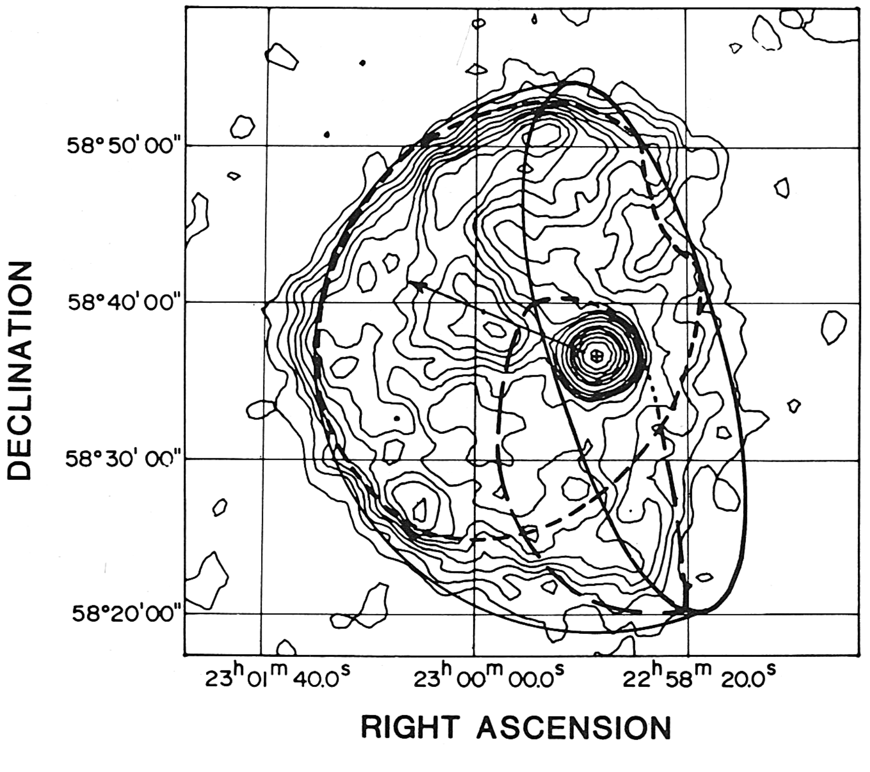


Figure 4. The precessing jet model superposed on the X-ray image obtained with the IPC detector of the Einstein Observatory. The precession axis of the jet model is indicated by the arrow.

DISCUSSION

It is clear from figure 3 that the precessing jet model provides a remarkedly good qualitative fit to the radio structure in view of the simple plane geometry assumed for the interaction of the supernova with the molecular cloud. This interaction surface is unlikely to be a smooth fat plane and the departures of the radio coutours from the fit close to

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the pulsar undoubtedly reflect this fact. In principle, it is possible, knowing the jet parameters, to extract a three dimensional cross section of this interaction surface close to the pulsar, from the radio observations.

One check of the model is to compare the orientation of the interacting molecular plane derived from the radio continuum structure with the CO contours of Israel (1980) and Heydari-Malayeri et al. (1981). The position angle of the derived plane agrees within 10° to the orientation of the CO contours along the western edge of the SNR.

We note that portions of the two radio loops predicted by the model are missing or very weak in the SW quadrant. Since there is considerable variation in the emission strength about the loops, these portions may simply be much fainter. The two brightest radio features are almost diametrically opposite each other which suggests they might reflect the present locations where the two jets are exciting the cavity walls. Also the tail like structure exhibited by the SW feature suggests a sense of rotation consistent with the counter-clockwise rotation implied by the X-ray emission from the eastern jet. The lifetime of the synchrotron emitting electrons in years is $\sim -0.85\ \nu^{-1/2}\ B^{-3/2}$, where $\nu$ is the observing frequency in GHz and B is expressed in gauss. For there to be a noticeable decay in the emission as a function of position from the present location of the jets the time scale of this decay must be comparable to or less than the precession period of the jets. For a precession period similar to that of SS 433, this would require large field strengths in the interaction region of $\sim 1$ gauss. Our existing radio observations taken over a time span of one year set an upper limit on possible rotation of the hot spots of < 5 degrees per year.

At X-ray wavelengths, it is apparent that we may be seeing emission from one of the jets or from gas heated by the jet along its path. We note that similar to SS 433 (Seward et al., 1980; Grindlay et al., 1983) the X-ray jet in G109.1-1.0 is most intense along the direction of the precession axis as derived from the radio observations (see figure 4). The model described in this paper requires that a second oppositely directed jet emerge from the pulsar on the western side. Why is no X-ray emission detected from this jet? A close examination of the X-ray emission indicates that there is a gap in the X-ray emission in the eastern jet extending from the pulsar out for an angular distance of $\sim 6$ arcmin. We note that a similar gap is observed in the X-ray emission from the SS 433 jets (Grindlay et al., 1983). On the western side of G109.1-1.0, the X-ray and radio emission declines rapidly and disappears completely at an angular distance of 8.5 arcmin from the pulsar. Thus at the point where we might expect to see X-ray emission from a western jet, the X-ray emission has all but disappeared from the nebula as a whole. The disappearance of the radio emission as well argues that this is not just X-ray absorption by the cloud although that may be partly the case. Thus the present X-ray observations do not rule out the existence of a western jet.

In spite of the parallels that have been drawn between the jet structure of SS 433/W50 and that proposed for 1E 2259+586/G109.1-1.0 it is important to note the significant differences that exist between the two central objects. SS 433 does not exhibit X-ray pulses and while the X-ray luminosities of the two objects are similar the ratio of optical to X-ray luminosity is more than 1000 times greater for SS 433. In addition the upper limit on the radio flux density of 1E 2259+582 of $\lesssim$ 200 μJy (Gregory et al., 1982) implies a radio luminosity more than 3000 times greater for SS 433. The X-ray, radio and optical properties of 1E 2259+586 are in fact much more like those of low mass close binary X-ray sources which are not known to exhibit jets. If 1E 2259+586 is a member of this class it is the first one to be found in association with a SNR.

At X-ray wavelengths both G109.1-1.0 and the SNR W50 show evidence for a large scale jet like feature emerging from the central source. In the case of SS 433/W50 there is direct radio and optical evidence for the existence of twin precessing jets which interact with the SNR. In this paper, we have shown how the existence of twin precessing jets from 1E 2259 + 586 could account for the observed radio structure of G109.1-1.0. A search for high velocity emission lines from the faint $m_B$ = 22, optical counterpart of the pulsar reported by Fahlman et al. (1982) may help to confirm this picture.

The precessing jet model presented here may account for the radio structures of a number of other supernova remnants. In particular the SNR DA 530 is an obvious candidate and we recommend X-ray observations of this remnant to search for a central compact source and jet. This research was supported by grants from the Canadian Natural Science and Engineering Research Council. The NRAO is operated by Associated Universities Inc. under contract with the NSF.

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