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BEAM MODELS FOR SS 433

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ABSTRACT

We analyze the energetics of models for SS 433 which derive the large oscillatory Doppler shifts from the 164 day precession of a pair of oppositely directed beams. We propose that the beams power the emission lines (both shifted and unshifted), the compact X-ray source, and the radio source by dissipating a small fraction of their kinetic energy as they sweep through an ambient gaseous medium. An X-ray photoionization model fits the data well. The beams are also responsible for the elongated shape and filled-in structure of the extended radio source W50. From these two manifestations, we infer that the luminosity in kinetic energy in each beam exceeds 10^{40} ergs s^{-1}, five orders of magnitude greater than the Hα luminosity.

Two plausible sources of this energy are accretion and rapid rotation. Rapid rotation ($P \lesssim 10$ ms) of a magnetic neutron star can account for the strong, highly organized magnetic field permeating W50. Any of several processes may excite a wind, which is then collimated to form a pair of beams along the rotation axis. General relativistic geodetic or Lense-Thirring precession of the rotation axis due to a compact binary companion (orbital separation $\sim 10^{10}$ cm) or a sufficiently massive accretion disk gives rise to the 164 day period. The required binary period is 4–8 minutes, the shortest ever encountered; to simultaneously explain the observed 13 day period, SS 433 must be a triple system.

Our principal predictions are: (i) possible periodic variations corresponding to the rotational and orbital periods; (ii) an ϵ^{-2} photon spectrum in X-rays extending from ~ 1.7 keV to > 50 keV with a flux $\gtrsim 10^{35}(d/3.5 \text{ kpc})^2$ ergs s^{-1} per logarithmic band; (iii) an upper limit to the dereddened shifted He II $\lambda 4686$ emission of three orders of magnitude less than shifted Hα; (iv) beams resolvable by VLBI at $\sim 10^{-1}$ arcsec resolution; these will be found to precess with a 164 day period about the long axis of W50.

Subject headings: stars: binaries — stars: emission-line — stars: individual — stars: neutron

I. INTRODUCTION

The emission line object Stephenson-Sanduleak 433 (Stephenson and Sanduleak 1977) exhibits redshifted and blueshifted emission line systems which oscillate across the spectrum with amplitudes corresponding to Doppler shifts of more than 45,000 km s^{-1} (Margon *et al.* 1979*b*; Liebert *et al.* 1979). There is now little doubt that the shifts arise kinematically (Liebert *et al.* 1979; Abell and Margon 1979). Several kinematic models have been proposed (Abell and Margon 1979; Milgrom 1979), but those attributing the periodic Doppler shifts to orbital motion fall prey to a number of serious objections (Abell and Margon 1979; Fabian and Rees 1979; Katz 1979). We shall argue that the shifted lines arise from gas accelerated in a relatively compact region which radiates much farther out. The simplest such model involves two collimated gaseous streams emerging in opposite directions from some unspecified central object (Abell and Margon 1979; Milgrom 1979; Fabian and Rees 1979). To explain the oscillations Abell and Margon (1979) and Martin, Murdin, and Clark (1979) have shown that every 164 days the beams must describe either a cone of half-opening angle 17° about an axis 78° from the line of sight, or the same thing with the angles interchanged.

Our purpose in this paper is to explore constraints that the observations place on physical conditions in SS 433, and to follow a chain of inferences to what we think is a likely astrophysical model. We shall assume that the object is galactic with $d \gtrsim 3.5$ kpc, and is reddened by $E_{B-V} \gtrsim 1.4$ (Margon *et al.* 1979*b*). A useful model should account for the absolute and relative intensities of the various emission lines, the velocity structure of the beams, the 164 day period, and the possible influence of SS 433 on its environment, as manifested by the extended radio source W50.

Accordingly, we begin in § II with a description of the main spectral features we seek to explain, and find some general constraints which they impose on the beams and the gas responsible for the rest emission. In § III we consider specific excitation models, and argue that both the shifted and unshifted lines are excited by

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the interaction of the beams with a local ambient medium. Most of the energy in the beams, however, is deposited in the surrounding interstellar medium where it produces the supernova remnant–like radio source W50. We are impressed by the fact that SS 433 is exactly centered on W50, and in § IV we describe how W50's unique features may be accounted for by the action of the beams. The fact that the beam velocity is reasonably constant at $0.27c$ strongly suggests that the beams are accelerated hydrodynamically in the vicinity of a compact object. The high magnetic pressure in W50 and large kinetic luminosity suggest that SS 433 contains a rapidly rotating neutron star. We outline several models for producing and collimating the beams in § V. The 164 day period and the geometry of the oscillations in beam direction find a natural explanation as the geodetic precession of the neutron star by a binary companion (§ VI). In the conclusions (§ VII), we discuss the evolution of SS 433 and summarize the predictions made by our model.

II. CONSTRAINTS ON LINE EMISSION

Characterize the emitting region of each beam by a length l and a width θl. We shall assume that the length is comparable with the distance of the emitting region from the beam source, so θ is effectively the opening angle of the beam. The fact that the observed widths of the shifted lines do not exceed 10% of their displacements then implies

$$\theta \lesssim 0.1 \text{ radians} .$$

Both the shifted and unshifted lines exhibit large variations of intensity and profile on time scales as short as 1 day. By the usual light travel time argument, this indicates a maximum size of 2.6×10^{15} cm for both emitting regions. If coherent fluctuations are transmitted at the beam speed, $V_B = 0.27c$, then l must not exceed 7×10^{14} cm. These upper limits on l also guarantee that the lines will not be excessively broadened by spiraling of the beam pattern. Henceforth we shall parametrize l and the distance from the beam origin, r, in units of 10^{15} cm, and we shall parametrize θ in units of 0.1 radians.

The blackbody limit gives a lower limit to the sizes of the emitting regions. Assuming that the emission is thermal, the intensity at line center cannot exceed $\pi\theta l^2 B_\lambda(T)$, where $B_\lambda(T)$ is the Planck function evaluated at the kinetic temperature of the emitting region. This implies

$$l > 1.6 \times 10^{12} \theta^{-1/2} T_4^{-1} (L_{\mathrm{H}\alpha})_{35}^{1/2} \text{ cm} , \qquad (1)$$

where the Hα luminosity of each beam is $(L_{\mathrm{H}\alpha})_{35} \equiv L_{\mathrm{H}\alpha}/10^{35}$ ergs s^{-1} $\sim 0.5(d/3.5 \text{ kpc})^2$, $E_{B-V} \gtrsim 1.4$, and $T_4 = T/10^4$ K cannot be much greater than unity, to avoid exceeding the observational upper limit on He II emission. This upper limit strongly constrains acceptable models for the excitation mechanism; however, the weakness of He II emission is a natural consequence of our model (§ III). The unshifted and shifted lines have similar equivalent widths and, by the blackbody argument, the unshifted lines must come from a region larger than 10^{11-12} cm across. These lines characteristically have cores of half-width ~ 500 km s^{-1} and wings of half-width ~ 1000–2000 km s^{-1}, with roughly comparable equivalent widths in each. To explain the line widths in terms of bound motions in a gravitational potential, the associated central mass would have to be greater than $10\, M_\odot$ for the cores and greater than $150\, M_\odot$ for the wings; otherwise the unshifted line widths reflect outflow or the interaction of ambient gas with the beams (see § III). In any case, outflow at 365 km s^{-1} is manifest in P Cygni absorption profiles notched into the unshifted He I and Hβ lines (Margon *et al.* 1979*b*).

In general the beams will be nonuniform. Let f be the volume filling factor of the clumps comprising the beams.[3] Then the total Hα luminosity from each beam may be written

$$L_{\mathrm{H}\alpha} = 2.5 \times 10^{40} \alpha \zeta^2 \eta f n_{11}^2 \theta_{0.1}^2 l_{15}^3 T_4^{-1/2} \text{ ergs s}^{-1} , \qquad (2)$$

where n_{11} is the density of the emitting gas in units of 10^{11} cm^{-3}, f is the volume filling factor, η is the fraction of the beam's cross section involved in emission, $\zeta \equiv [n_p/(n_p + n_{\mathrm{H}})]$ is the ionized fraction, and

$$\alpha \approx 1 + 1.72 \times 10^5 \left(\frac{1-\zeta}{\zeta}\right) T_4^{1/2} \times \exp(-14.02/T_4) \qquad (3)$$

is the factor by which $L_{\mathrm{H}\alpha}$ is enhanced over the pure recombination value. The kinetic luminosity of line emitting gas in each beam is

$$L_B = 3.5 \times 10^{44} f n_{11} \theta_{0.1}^2 l_{15}^2 \left(\frac{V_B}{0.27c}\right)^3 \text{ ergs s}^{-1} . \qquad (4)$$

Since $L_{\mathrm{H}\alpha} \gtrsim 5 \times 10^{34}$ ergs s^{-1} and $\alpha\zeta^2$ cannot greatly exceed unity, beam densities greater than 10^8 cm^{-3} are necessary to avoid a kinetic luminosity exceeding 10^{42} ergs s^{-1}. In any case, the lack of forbidden lines in both the shifted and unshifted systems implies that the

[3] Spectra kindly supplied to us by J. Thorstensen and P. Charles support our hypothesis of a lumpy beam structure, and also provide clues to the nature of the acceleration mechanism and the dimensions of the shifted emission regions. In these spectra, the wavelength variation of the shifted lines does not always appear to occur continuously. Sometimes individual components of the line profile brighten and fade, *while the wavelength of their line emission stays fixed.* The wavelength variation of the entire line profile proceeds by the fading of older components at one wavelength, and the emergence of new components at slightly different wavelengths. We identify the individual components with distinct clumps of gas in the emission regions. The constancy of their wavelengths implies that the emitting gas is moving ballistically and that the acceleration to $V_B = 0.27c$ occurs prior to the emission. Thus, models in which the Doppler shifts result from infall, rotation, or orbital motion are excluded. The lifetimes of individual components are typically days, so that the length of the emitting region is roughly 10^{15} cm. Blair and Kirshner (private communication) have also noticed features with this behavior in their data on SS 433.

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densities in all emitting regions must exceed $\sim 10^6$ cm^{-3}.

III. EXCITING THE LINES

Energy, in forms capable of exciting and ionizing atoms, must be supplied continuously to the line-emitting gas in SS 433. The supply to the beams may come from an external source, or may arise locally through the dissipation of the beams' kinetic energy. In this section we discuss several possible excitation models, and develop in detail the one which seems most promising.

As an example of the problems inherent in external excitation schemes, consider direct UV photoionization of the beams by a compact (dimensions of an O star or smaller) isotropic continuum source at the center of the SS 433 system. To such a source, the emitting region of each beam would cover only a small fraction ($\sim \theta^2/4\pi$) of the sky, and the ionizing luminosity would have to exceed $L_{\mathrm{H}\alpha}$ by a factor of at least $10^4 \theta_{0.1}{}^{-2}$. This luminosity is much greater than the combined output of SS 433 in all observed bands. Unfortunately, we cannot rule out such a large luminosity emerging in UV, since the heavy extinction would hide the source from current detectors. An additional drawback to this sort of model is its difficulty in producing comparable equivalent widths in the shifted and unshifted systems.

It seems more natural to use the ample kinetic energy in the beams (eq. [4]) to excite the line emission. This energy can be tapped either by internal dissipation within the beams or by the beams' interaction with ambient gas. The former possibility was considered by Fabian and Rees (1979), who have suggested a dissipation scheme in which velocity fluctuations in the beams steepen into shocks, the radiation from which powers the lines. If δv is the rms velocity fluctuation, then the maximum conversion efficiency for beam kinetic energy into Hα is $\lesssim 0.1(\delta v/V_B)^2$. The cooling shocks radiate EUV and X-rays which are then absorbed by the already cooled gas behind the shocks, as in the model of Daltabuit, MacAlpine, and Cox (1978) for broad emission lines in quasars. In order for He II λ4686 to have less than half the strength of He I λ5876 (at the source) in the shifted line systems, δv must not exceed ~ 110 km s^{-1} (Shull and McKee 1979), indicating that the beam must have a kinetic luminosity of at least $2 \times 10^{41}(d/3.5 \text{ kpc})^2$ ergs s^{-1} for this model to work. This model also does not readily explain the comparable equivalent widths in the shifted and unshifted lines, since the excitation is confined mainly to the beam gas.

The alternatives to self-induced dissipation involve some kind of interaction between the beams and an ambient medium. As each beam sweeps through the ambient gas (density n_A) with pattern speed $V_p \approx 1300 r_{15}$ km s^{-1}, it shocks the ambient gas and dissipates its kinetic energy at a rate $\sim \frac{1}{2} m_p n_A V_p{}^3 \theta r^2$. Simultaneously, the lumpy beam may entrain a fraction, f_{ent}, of the swept-past ambient material, accelerating it to the beam speed and dissipating energy at a rate $\sim \frac{1}{2} m_p n_A V_B{}^2 V_p f_{\mathrm{ent}} \theta r^2$. In the latter case, the primary excitation process is ionization by fast particles, while in the former it is photoionization by EUV and X-rays produced in the shock and subsequent collisional ionization and excitation by suprathermal photoelectrons.

We will concentrate here on the former possibility and show that excitation by shock-produced X-rays and EUV accounts for most of the general features of the SS 433 spectrum in a natural and self-consistent way. The properties of the model depend on both the emissivity of the shocked ambient gas and the opacity of the beam. Because He II λ4686 is weak, we can assume that recombination times are short compared with ionization times (Tarter and Salpeter 1969) and the absorption cross section per H atom is given (to within a factor ~ 2) by (Cruddace *et al.* 1974)

$$\sigma \approx 1.73 \times 10^{-22} \epsilon_{\mathrm{keV}}{}^{-8/3} \text{ cm}^2 , \quad 13.6 \text{ eV} < \epsilon < 12.4 \text{ keV} , \tag{5}$$

for cosmic abundances, where ϵ_{keV} is the photon energy. (Reasonable metal abundances are indicated by the presence of unshifted O I λ8446 [Margon *et al.* 1979*a*] and a 6.8 keV Fe line [Marshall *et al.* 1979]; but even if metals were entirely absent, the cross section would be lower by less than an order of magnitude at $\epsilon \lesssim 1$ keV.) A fraction $\delta \lesssim 0.1$ of the absorbed energy comes out in Hα. The temperature of the shocked ambient gas is $T_x \approx 2 \times 10^7 r_{15}{}^2$ K, and its emissivity is described by a line-dominated cooling function $\Lambda \sim 6.2 \times 10^{-19} T_x{}^{-0.6}$ ergs cm^3 s^{-1} for $T_x < 4 \times 10^7$ and cosmic abundances (McKee and Cowie 1977), and by bremsstrahlung at higher temperatures or low metal abundances.

Since δ is nearly constant, the local Hα emissivity is simply proportional to the incident ionizing flux times the absorbed fraction q. Because σ depends steeply on ϵ, the beam may be opaque to the entire spectrum ($q = 1$) at small r, but will absorb the incident radiation only up to some $\epsilon_{\mathrm{abs}} < \epsilon_x$ at large r. Similarly, the ambient gas can cool behind the shock when the beam crossing time $\theta r/V_p = 7.7 \times 10^5 \theta_{0.1}$ s exceeds the cooling time, which is always true at small r. Radiation is then produced at the dissipation rate $L_x \sim \frac{1}{2} m_p n_A V_p{}^3 \theta r^2 \propto n_A r^5$, and the H$\alpha$ emissivity per unit length, $dL_{\mathrm{H}\alpha}/dr$, must increase steeply with r for any reasonable run of n_A. At large r, however, L_x drops below the dissipation rate by a factor $t_{\mathrm{cross}}/t_{\mathrm{cool}}$, and either increases or decreases with r, depending on the run of ambient density. To explain the P Cygni profiles (see § II), we suppose that the ambient medium is blowing out in a constant velocity wind, $n_A \propto r^{-2}$; we can then show that $dL_{\mathrm{H}\alpha}/dr$ must decrease faster than $1/r$ at large r. Thus, the size l of the emitting region of the beam is characterized by the condition $t_{\mathrm{cross}} \approx t_{\mathrm{cool}}$, which determines the ambient density in terms of l:

$$n_A \approx 9 \times 10^7 \theta_{0.1}{}^{-1} l_{15}{}^{3.2} \text{ cm}^{-3} . \tag{6}$$

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The radiation flux is the dissipation rate

$$L_x \simeq 2 \times 10^{37} l_{15}{}^{8.2} \text{ ergs s}^{-1}, \quad (7)$$

and the absorbed fraction is related to L_x by $q = 2L_{\mathrm{H}\alpha}/\delta L_x$. We have assumed above that line cooling dominates in the Hα emitting region.

We will assume that the line-emitting gas in the beam is in pressure balance with the shocked ambient medium; we will subsequently show that this assumption is self-consistent. Then $n_{11} = 30 T_4{}^{-1} \theta_{0.1}{}^{-1} l_{15}{}^3$. If the beam is opaque to all photons with $\epsilon < \epsilon_{\rm abs} \leq \epsilon_x$, i.e.,

$$\eta f n \sigma(\epsilon_{\rm abs}) \theta l = 1, \quad (8)$$

then $q \approx \epsilon_{\rm abs}/\epsilon_x$ for line cooling with $\epsilon_{\rm abs}/\epsilon_x \gtrsim 0.1$ (Tucker and Koren 1971), and equation (8) implies

$$500(\alpha\zeta^2) q^{5/3} l_{15}{}^{13/3} \left(\frac{0.1}{\delta}\right) T_4{}^{-3/2} \approx 1. \quad (9)$$

Detailed numerical calculations (Hatchett, Buff, and McCray 1976; Tarter and Salpeter 1969) indicate that ζ is determined by direct photoionization-recombination balance involving the lowest photon energies present ($\epsilon_{\rm abs}$) when $\zeta \gtrsim 0.1$ and by collisional ionization when $\zeta \lesssim 0.1$; hence

$$\frac{\zeta^2}{1-\zeta} \approx \max \begin{Bmatrix} 5 \times 10^{-8} T_4{}^{3/2} l_{15}{}^{-19/3} q^{-8/3} \\ 10^{-2} \end{Bmatrix}. \quad (10)$$

Using (7) to substitute q for l, we find that ζ drops below 0.1 when q exceeds 10^{-2}. The low temperature ($T_4 < 2$) at this point (Hatchett, Buff, and McCray 1976; Tarter and Salpeter 1969) implies that $\alpha < 2$ (eq. [3]), and we conclude that (9) can be satisfied only if the beam is opaque to the entire ionizing flux, $q = 1$. The scale of the emitting region is then

$$l_{15} \approx 0.7 \left[\left(\frac{d}{3.5 \text{ kpc}}\right)^2 \left(\frac{0.1}{\delta}\right)\right]^{1/8.2}, \quad (11)$$

in excellent agreement with the beam travel time argument, and it is easily verified that the ambient medium at l is opaque as well. Inserting $l_{15} \approx 0.7$ into (9), we find

$$\alpha\zeta^2 \approx 10^{-2} \left(\frac{\delta}{0.1}\right) T_4{}^{3/2}, \quad (12)$$

corresponding to collisional excitation and ionization with T_4 close to unity. This result, which one would expect on the basis of the above mentioned numerical models, indicates *a posteriori* that the assumption of pressure balance between the shocked ambient gas and the beam is correct.

Our model automatically produces three important observed features of SS 433. First, the low ionization state (12) means that He II emission is very weak from the bulk of the emitting region. Some emission will come from the outer layers of the beam, where the lower optical depth allows helium to be doubly ionized. From our values above for L_x, T_x, l_{15}, and n_{11} we find that the ionization state here has [He III]/[He II] ≤ 0.1, [He II]/[He I] ≤ 3, and [H II]/[H I] ≤ 1 (Tarter, Tucker, and Salpeter 1969). We calculate a recombination luminosity $L_{4686} \leq 7 \times 10^{31} (d/3.5 \text{ kpc})^2 (0.1/\delta)$ ergs s^{-1}. For comparison, unshifted He I λ5876 is more than 75 times this luminous for $E(B-V) \geq 1.4$ mag (Margon *et al.* 1979*b*). Second, in the shifted line systems the He I triplet lines λ5876 and λ7065 are stronger relative to the singlet line λ6678 than is the case for the unshifted system. This is because in the predominantly neutral beam gas collisional excitation of upper triplet line levels from the 2 ^3P and metastable 2 ^3S levels (populated essentially by recombination) will dominate recombination, while much higher energy electrons are required to collisionally excite the upper singlet levels (MacAlpine 1976; Netzer 1978). Third, the fact that both the beam and the ambient medium are opaque to the entire ionizing flux and that each receives about one-half of this radiation implies that the shifted and unshifted line systems will have comparable luminosities.

We now discuss the physical conditions within the beams. Pressure balance implies

$$n_{11} \approx 4 \theta_{0.1}{}^{-1} T_4{}^{-1} \text{ cm}^{-3}, \quad (13)$$

while from (8) we obtain

$$f\eta \approx 3 \times 10^{-5} T_4. \quad (14)$$

We cannot separately determine η, the fraction of the beam which is radiating. However, we can place a lower limit on the kinetic luminosity in the beam (eq. [4]) by setting $\eta = 1$:

$$L_B \gtrsim 3 \times 10^{40} \theta_{0.1} \left(\frac{0.1}{\delta}\right)^{1/4} \left(\frac{d}{3.5 \text{ kpc}}\right)^{1/2} \text{ ergs s}^{-1}. \quad (15)$$

The corresponding mass loss rate is

$$7 \times 10^{-6} \theta_{0.1} \left(\frac{0.1}{\delta}\right)^{1/4} \left(\frac{d}{3.5 \text{ kpc}}\right)^{1/2} M_\odot \text{ yr}^{-1}.$$

We propose that the observed X-rays (Seward *et al.* 1976; Marshall *et al.* 1979) arise in the shocked ambient medium around the beams, in a region somewhat larger than the emission-line zone. The ambient medium is transparent to photons of energy $\epsilon_x(r) \approx 1.73 r_{15}{}^2$ keV for $r_{15} > 1$. To calculate the X-ray spectrum and luminosity we shall ignore the region where line cooling is important and focus on the region $T > 4 \times 10^7$ K, $r_{15} > 1.4$ where bremsstrahlung dominates. Here the X-ray luminosity per unit length

$$dL/dr \approx \tfrac{1}{2} m_p n_A V_p{}^3 \theta r \times (t_{\rm cross}/t_{\rm cool}) \propto r^{-1},$$

and we have a power law for the luminosity per unit energy

$$L_\epsilon = \int \frac{dL}{dr} \frac{e^{-\epsilon/kT(r)}}{kT(r)} dr \propto \epsilon^{-1} \quad \text{for } \epsilon \gtrsim 3 \text{ keV}.$$

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An explicit calculation of the 2–10 keV luminosity gives for the total from both beams

$$L_{2-10\,\mathrm{keV}} \approx 3 \times 10^{35}\left(\frac{0.1}{\delta}\right)\left(\frac{d}{3.5\,\mathrm{kpc}}\right)^2 \mathrm{ergs\,s^{-1}}\,.$$

Both the luminosity and predicted spectrum are in good agreement with the observations of Marshall *et al.* (1979). The ambient medium produces X-rays out to a radius $\sim 6 \times 10^{16}$ cm, where the pattern speed approaches the beam speed and the beam pattern is swept back. The shock speed at this radius is comparable with the beam speed, 0.27c, yielding cutoff energies ranging from $\gtrsim 50$ keV to upwards of 1 MeV, depending on how effectively the electrons are heated to postshock temperatures. Hence we predict that SS 433's ϵ^{-2} photon spectrum extends to very high energies.

Finally, we consider emission from the ambient medium. Comparable amounts of ionizing X-rays are absorbed by both unshocked material and the cooled ambient medium behind the shock. The latter moves at $\sim V_p$ and could account for the 1000–2000 km s^{-1} wings on the unshifted lines (§ II), while the cores would be filled in by emission from the unshocked gas. Since the densities in the two regions are very different, one might be able to test this interpretation by comparing the profiles of different lines.

IV. W50: THE "BEAMBAG"

SS 433 is at the center of the nonthermal radio source W50. According to Velusamy and Kundu (1974), W50 is a supernova remnant (SNR) with a flux of 32 Jy at 11 cm and with a remarkably high degree of polarization—up to 23% in the main body of the SNR and up to 35% in the eastern end. At the 3.5 kpc estimated distance of SS 433, W50 has a radius of about 30 pc. The minimum energy in relativistic electrons and magnetic fields is $5 \times 10^{49} R_{20}{}^{17/7}$ ergs, where R_{20} is the mean radius in units of 10^{20} cm ≈ 30 pc.

Inspection of their map of W50 reveals two remarkable features. First, there is a radio source centered on SS 433 (Clark and Murdin 1978; Ryle *et al.* 1978), and, although there is a ridge of emission to the northwest, the source is relatively filled in. This is reminiscent of the Crab Nebula, and we interpret this as evidence that magnetic field as well as high-energy particles are being injected into W50. This in turn is consistent with SS 433 being a neutron star.

The second remarkable feature is that W50 is elongated, with radio hot spots at either end. We interpret this as indicating that the beams are propagating in the direction of the elongation and are having a significant dynamical effect on the nebula: W50 is a "beambag." The linear rather than toroidal structure indicates that the precession angle of 17° rather than 78° is appropriate.

The radius of an adiabatic blast wave driven into the ISM by steady injection of a $\gamma = 5/3$ fluid is

$$R = 0.9(L/\rho_0)^{1/5} t^{3/5}\,, \qquad (16)$$

where L, the energy injection rate, equals L_B (Blandford and McKee 1976) in the case of W50. Measuring L in terms of 10^{40} ergs s^{-1} and the ambient density ρ_0 in units of 10^{-26} g cm^{-3} ($n \sim 5 \times 10^{-3}$ cm^{-3}), we find that the age of W50 is 9500 $(\rho_{-26} L_{40}{}^{-1} R_{20}{}^5)^{1/3}$ yr, its expansion velocity is 2000 $(L_{40}/\rho_{-26} R_{20}{}^2)^{1/3}$ km s^{-1}, and its energy is 3.0×10^{51} $(\rho_{-26} L_{40}{}^2 R_{20}{}^5)^{1/3}$ ergs. If one quarter of this energy is in magnetic field, then $B = 6.7 \times 10^{-5}$ $(\rho_{-26} L_{40}{}^2 R_{20}{}^{-4})^{1/6}$ gauss. If SS 433 was formed in a supernova explosion, then its age may be slightly less and its velocity and energy somewhat higher. It has a bremsstrahlung luminosity of 3.2×10^{33} $(\rho_{-26}{}^5 R_{20}{}^7 L_{40})^{1/3}$ ergs s^{-1}. Since there is no evidence that W50 is an X-ray source, we estimate $L_x \lesssim 10^{34}$ ergs s^{-1} at ~ 1 keV; either the expansion velocity is low ($L_{40} \ll 1$) and the resulting soft radiation from W50 is absorbed by the intervening matter or the expansion velocity is high enough to generate observable X-rays ($L_{40} \sim 1$) but the ambient density ρ is too low to give much luminosity. We favor the latter alternative and therefore argue that W50 is expanding into a low-density region of the ISM with $\rho_{-26} \lesssim 2$ ($n \lesssim 10^{-2}$ cm^{-3}).

The fact that the dynamical effects of the beams are visible implies $\rho_b V_b{}^2 \gtrsim Lt/(4\pi R^3/3)$, where ρ_b is the density of the beam when it reaches the edge of W50 and the right-hand side is the energy density inside W50. Let πa^2 be the effective area of beam when it impacts at the edge of the nebula: we estimate $a/R \sim 0.17$ from the map of Velusamy and Kundu (1974). Then $\rho_b v_b{}^2 = L/\pi a^2 v_b$ and the inequality becomes $(v/v_b) \gtrsim (9/20)(a/R)^2$, where v is the expansion velocity of the nebula. Using equation (16) to relate this to L, we obtain

$$L \gtrsim 5.8 \times 10^{43} R_{20}{}^2 \rho_{-26} (a/R)^6 \ \mathrm{ergs\,s^{-1}}$$

or

$$L \gtrsim 1.4 \times 10^{39} R_{20}{}^2 \rho_{-26} \ \mathrm{ergs\,s^{-1}}$$

for $a = 0.17R$, entirely consistent with our estimates above based on the Hα line emission.

V. BEAM SCHEMES

Theoretical models for the production of the beams in SS 433 must satisfy a number of observational constraints. They must produce two beams, oppositely directed, of gas with roughly cosmic abundances. The beams' velocity, 0.27c, must be stable to $\pm 10\%$ over time scales of days with smaller variations from the mean on longer time scales, and the beams' axis must precess with a 164$^{\mathrm{d}}$ period (Milgrom 1978; Margon *et al.* 1979*a*). We have argued in the preceding sections that the observations imply that the beams must be collimated to an opening angle $\theta \lesssim 5°$ and that

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they possess large kinetic luminosities, $L_B \gtrsim 3 \times 10^{40}$ ergs s^{-1}.

That the beams' velocity is mildly relativistic and not ultrarelativistic suggests that they are hydrodynamically accelerated near the surface of a compact object (Katz 1979).

Two plausible sources of the beam energy are accretion and rapid rotation. Martin and Rees (1979) have outlined a model involving accretion by a spinning black hole. We note here that since L_B probably exceeds the Eddington limit for a solar mass object by 1–3 orders of magnitude, the accretion flow would have to be supercritical even if the black hole mass exceeded 10 $M_\odot$. Dragging of inertial frames due to the black hole's spin will align the inner accretion disk with the equatorial plane as described by Bardeen and Petterson (1974), thus selecting the spin axis as the beam axis. Whether outflowing material can be accelerated and collimated in the inner regions of a supercritical accretion disk is unknown, although investigations are underway (Paczyński and Wiita 1979; Begelman and Meier, in preparation).

The only likely rotational energy source is a rapidly spinning neutron star. White dwarfs cannot store enough rotational kinetic energy to inflate W50, while extraction of rotational energy from a black hole probably proceeds by acceleration of ultrarelativistic particles (Blandford and Znajek 1977). To satisfy the overall energy budget, the neutron star (NS) must have had an initial spin period shorter than about 5 ms, so that the initial rotational energy E_{rot} exceeded $8 \times 10^{50} I_{45}$ ergs, where I_{45} is the moment of inertia of the NS in units of 10^{45} g cm^2. The corresponding lifetime is $E_{\text{rot}}/L \sim 3000 L_{40}{}^{-1}$ yr, where the kinetic luminosity L is not necessarily related to the magnetic dipole luminosity commonly applied to pulsars since the NS is not in a vacuum.

Several schemes can be proposed to extract rotational energy from a rapidly spinning magnetized neutron star—these have the added virtue of accounting for the large magnetic energy filling W50. Angular momentum is transferred to matter at the magnetopause (inside the light cylinder) by magnetic torques exerted via currents circulating along field lines from the magnetopause through the NS and back. Energy may be extracted in this process by Joule heating associated with these currents, either at the magnetopause or within the NS. In addition, transfer of angular momentum implies an increase in the rotational kinetic energy of matter at the magnetopause which may be dissipated in shocks and Alfvén waves (the so-called propeller effect: Davidson and Ostriker 1973; Illarionov and Sunyaev 1975).

In normal pulsars the low surface temperatures observed indicate that the flow of current through the star is only weakly dissipative. The resistivity of the crust is, however, a strongly increasing function of temperature. Strong Joule heating would result in a thermally supported atmosphere forming on the polar field lines. If this atmosphere cannot radiate its energy away fast enough, it will be accelerated outward as a stellar wind constrained to follow the field lines out to the magnetopause, R_A. When the sonic surface $R_s < R_A$, we expect the flow outside R_A to be essentially ballistic. The configuration of the magnetopause will depend on whether the kinetic energy density there is dominated by the component of velocity along the field (thermally driven) or by the component perpendicular to the rotation axis (centrifugally driven: Mestel 1968). In either case, we expect the sonic point to lie near the NS surface, giving the wind a terminal speed close to the beam speed ($\sim v_{\text{escape}}$ from a NS).

The centrifugally driven wind is subject to positive feedback (Arons 1979). Torques exerted on the wind require opposing torques in the NS via return currents which dissipate energy, heat the surface and drive off more wind. Also, as the NS crust heats up, the resulting increase in resistivity causes still more heating. However, the wind is uncollimated since it must carry away angular momentum as well as energy. To provide collimation, we must appeal to the ambient gas surrounding the magnetosphere, which may form a collimating channel aligned with the spin axis of the neutron star, provided it has angular momentum and is not accreting rapidly (Bardeen and Petterson 1974). Additional collimation may occur further out as well, if the pressure of the ambient medium decreases slowly enough with radius r that the opening angle of the channel decreases with r (Blandford and Rees 1974). The thermally driven wind may be collimated by the magnetic field itself if the NS is an aligned rotator and the dissipation is sufficiently concentrated near the polar caps. Here the ambient gas must absorb angular momentum, but a significant fraction of the rotational *energy* goes into heating material on the surface of the neutron star.

Models which make the beam from NS surface material face serious composition problems. Unless a layer of hydrogen and helium resides on the surface of the neutron star, or photodissociation within the wind breaks down most of the heavy elements, these processes cannot produce the observed beams in SS 433. We can avoid these problems by supposing that the beams form from ambient material heated at the magnetopause, either by dissipation of currents or by the development of a turbulent shear layer. In principle the resulting outflow can have a kinetic energy flux exceeding the Eddington limit by the requisite amount, and speeds as great as the rotation speed of the magnetopause, i.e., not much smaller than c if R_A lies close to the light cylinder. Collimation could occur as for the centrifugally driven wind.

VI. TORQUING THE NEUTRON STAR

In the previous sections, we have argued that the power source behind SS 433/W50 is a rapidly rotating neutron star. Thus, the 164 day period observed in the velocity curve of the system cannot result from rotation. The relative stability of the redshift variations

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suggests that the beams in SS 433 are ejected along the axis of the neutron star.

The redshift variations in SS 433 then require that the axis precess through an angle of 17° with a period of 164 days. This cannot be free precession, because the period of free precession observed in an inertial frame is always nearly the period of rotation for a moderately symmetric object. A precessional torque could result from the interaction of the neutron star magnetic field and ambient gas; for example, it could be an accretion torque. However, it is unlikely that this process would produce a simple stable precession.

We propose that the precession of the NS in SS 433 results from the gravitational effects of a binary companion. There are two significant effects that can cause precession of a rapidly rotating NS in a very close binary. They are the classical torque due to the oblateness of the rotating star, $N_{\rm OB}$, and the general-relativistic geodetic precession (de Sitter 1916; Misner, Thorne, and Wheeler 1973; Martin and Ress 1979). The geodetic precession frequency of a neutron star of mass M orbiting a companion of mass m is

$$\omega_{\rm GP} = \frac{4\pi G}{c^2 a P_{\rm orb}}\left(\frac{mM}{m+M}\right)\left(1+\frac{3}{4}\frac{m}{M}\right), \tag{17}$$

where a is the orbital separation, and $P_{\rm orb}$ is the orbital period. The classical torque on the rotational oblateness of the NS gives a precession frequency

$$\omega_{\rm OB} = -3\pi \frac{P_{\rm rot}}{P_{\rm orb}^2}\frac{m}{m+M}\frac{\Delta I}{I_p}\cos\theta_p\,. \tag{18}$$

In equation (18), $\Delta I = I_p - I_e$, where I_p and I_e are the polar and equatorial moments of inertia of the NS and θ_p is the angle between the binary orbital angular momentum and the rotational angular momentum of the NS. The frequencies are additive in the post-Newtonian approximation; the minus sign in equation (18) indicates that they have the opposite sense for prograde rotation. For a NS rotating as rapidly as possible before the onset of barlike instabilities, and in a very close binary, the two frequencies are comparable. For a lower rotation rate and somewhat larger binary the geodetic precession dominates. We will assume, therefore, that the precession of SS 433 is geodetic. From equation (17), the required orbital parameters a and $P_{\rm orb}$ are

$$a = 9\times 10^9\left(\frac{P_{\rm prec}}{164\ {\rm d}}\right)^{2/5}\left(\frac{M}{M_\odot}\right)^{3/5} x^{2/5}(1+\tfrac{3}{4}x)^{2/5} \times (1+x)^{-1/5}\ {\rm cm}\,, \tag{19}$$

$$P_{\rm orb} = 7.8\left(\frac{P_{\rm prec}}{164\ {\rm d}}\right)^{3/5}\left(\frac{M}{M_\odot}\right)^{2/5} x^{3/5}(1+\tfrac{3}{4}x)^{3/5} \times (1+x)^{-4/5}\ {\rm minutes}\,, \tag{20}$$

where $P_{\rm prec}$ is the observed precession period and $x \equiv m/M$ is the mass ratio in the binary. Thus, if SS 433 is a gravitationally precessing NS, the binary period is the shortest ever encountered. For such a short-period binary, the lifetime $t_{\rm GR}$ due to gravitational radiation can be rather short; from equation (20) we find

$$t_{\rm GR} = 4.3\times 10^4\left(\frac{P_{\rm prec}}{164\ {\rm d}}\right)^{8/5}\left(\frac{M}{M_\odot}\right)^{1/15} x^{9/15}(1+\tfrac{3}{4}x)^{8/5} \times (1+x)^{-9/5}\ {\rm yr}\,. \tag{21}$$

Happily, this is somewhat longer than the age of W50 derived in § IV.

Gravitational precession has several advantages over other mechanisms for producing precession in a rapidly rotating star as both $\omega_{\rm GP}$ and $\omega_{\rm OB}$ do not decrease as the rotation rate increases. (Actually, $\omega_{\rm OB}$ *increases* because $\Delta I/I_p \propto P_{\rm rot}^{-2}$). Moreover, as long as the binary period is much shorter than the precession period, both of the above mechanisms affect the rotational angular momentum *only* through simple precession.

Geodetic precession has a special advantage over any external torques, including the gravitational torque due to oblateness. Because it results from the parallel transport of the rotational angular momentum vector, it precesses all components of the NS at the same rate. In a NS more massive than about 0.5 $M_\odot$, the interior of the star is a neutron superfluid which is only weakly coupled to the solid crust (Baym *et al.* 1969). Physical torques will cause the crust and core to precess separately, and the weak dissipative coupling between the two will bring the neutron star and binary axes into alignment. If $t_{\rm prec}$ is the precession period of the crust relative to the core ($\gtrsim 50$ yr for $P_{\rm rot} \sim 5$ ms), then the damping time scale is roughly the coupling time scale, $t_{\rm couple}$, when $t_{\rm prec} \lesssim t_{\rm couple}$, and $t_{\rm prec}^2/t_{\rm couple}$ when $t_{\rm prec} \gg t_{\rm couple}$ (Sarazin, in preparation). Both theoretical calculations and pulsar observations indicate that the core-crust coupling time is on the order of days to years (Ruderman 1972). For the parameters relevant to our model, the precession due to oblateness torques is so slow that the damping time is comparable with the lifetime of the system. Geodetic precession is the only mechanism which can maintain the long-term precession of a massive NS; any physical torque can precess only a low-mass neutron star.

The recent discovery of a 13 day period in the radial velocity of the unshifted lines (Crampton, Cowley, and Hutchings 1979) does not invalidate our interpretation of the 164 day period as resulting from geodetic precession. The amplitude of the 13 day oscillation, 77 km s^{-1}, is consistent with the orbital parameters of typical X-ray binaries. We therefore suggest that SS 433 may be a triple system, with the tight binary described above in orbit about a normal star. Alternatively, general-relativistic precession of the compact object could be induced by a massive accretion disk, rather than by a close binary companion. Such a scenario, in which the disk material is supplied by Roche-lobe overflow of the 13 day binary companion, is under investigation by Sarazin, Begelman, and Hatchett (in preparation).

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VII. CONCLUSIONS

We combine a wide range of physical processes in our model for SS 433. Wherever possible, we have stressed how they fit together into a single coherent picture. However, it is equally important to stress that they are not inextricably intertwined—any one of this paper's sections could stand without the others.

Our model for the excitation of emission lines is most closely tied to observation. Kinetic energy is dissipated as the precessing beams sweep through the ambient medium. The shocked ambient gas cools by emitting X-rays, which excite emission lines in both the ambient and beam gases. Given the luminosity in shifted Hα and the opening angle of the beams (inferred from line widths), the model correctly reproduces the size of the emission region ($\sim 7 \times 10^{14}$ cm, known independently from line substructure and variability timescales), the rough equality of equivalent widths in the shifted and unshifted systems, the weakness of shifted He II emission, and the peculiar core-wing profiles of the unshifted lines. We calculate that the dense line-emitting material fills only a fraction $\sim 2 \times 10^{-4}$ of the beams' volume, yet each beam carries $\gtrsim 10^{40}$ ergs s^{-1} in kinetic energy, and $\gtrsim 10^{-5}\, M_\odot$ yr^{-1} in mass. The model also accounts remarkably well for the 2–60 keV intensity and spectrum observed by Marshall *et al.* (1979).

In our model, the velocity variations in SS 433 result from the geodetic precession of a rapidly rotating neutron star in a close binary. Geodetic precession, which is simply due to the parallel transport of the angular momentum vector, is shown to be the only mechanism capable of maintaining precession in a solar mass neutron star. The required binary period and separation are $P_{\rm orb} = 4$–8 minutes and $a = 0.7$–1.2×10^{10} cm. Obviously, the binary companion must be a white dwarf, NS, or black hole. The gravitational radiation lifetime of the system is 10^4–10^5 years, which is somewhat longer than the age of SS 433 deduced from W50.

Since the required binary separation is too small to contain two main sequence stars, the binary must have been formed with a much larger separation ($a \lesssim 10^{13}$). Let us assume that both stars were of moderate mass (between 1 and 4 $M_\odot$). When the companion star evolved off the main sequence, resulting in a common envelope binary, the white dwarf spiraled in due to accretion drag and loss of orbital angular momentum to the outer envelope. After it had accreted sufficient additional mass to exceed the Chandrasekhar limit, the white dwarf collapsed to form a NS. A substantial portion of the common envelope was blown away in the resulting supernova, but the inner envelope expanded and now surrounds the NS. This gas envelope produces the stationary line emission and continuum in the spectrum of SS433. The interaction between the beams and the envelope excites the moving line emission, and also produces the X-ray and radio emission. The remaining degenerate core of the binary companion causes the precession of the NS.

SS 433's association with W50 provides an important link between the beams' dynamics and that of the central source. W50's elongated shape and filled-in radio structure are evidence for continuing excitation by the beams, while the strong polarization and high minimum energy density suggest that magnetic field is continuously being injected by a rapidly rotating neutron star, as in the Crab Nebula. The age and total energy of W50 are consistent with the lifetime of the binary and rotational energy content of the neutron star, while the energy output is comparable with that inferred for the beams from the excitation model. The radio morphology of W50 resolves the kinematic ambiguity in the beam model for SS 433, indicating that the precession angle is 17°, rather than 78°.

Much work remains to be done on the acceleration of the beams. We have argued that the beams originate in a hydrodynamically accelerated wind powered by the rapid rotation of a neutron star, for three reasons: (1) the beam speed ($0.27c$) is close to the escape speed from a neutron star, indicating hydrodynamic rather than electrodynamic acceleration; (2) we need energy fluxes greatly exceeding the Eddington limit for a 1 $M_\odot$ object, hence accretion is an unlikely energy source; (3) the magnetic energy content of W50 suggests injection of magnetic field by a rapidly rotating neutron star. Although we have outlined several ways in which such a wind might arise, its details depend crucially on the physical conditions at both the magnetopause and the surface of the NS, which are not well known. To produce the narrow beams observed in SS 433, the wind must be collimated, perhaps in part as it passes through the ambient gas (Blandford and Rees 1974).

Our model makes several predictions. One of these is the possibility of periodic variations in the source emission with time scales corresponding to the binary period $P_{\rm orb} \sim 4$–8 minutes and the neutron star rotation period $P_{\rm rot} \sim 10$ ms; however, the presence of the gaseous envelope may obscure these variations. From the line excitation model, we predict that the ϵ^{-2} photon spectrum in X-rays extends at least to $\gtrsim 50$ keV and possibly as far as ~ 1 MeV, with a total flux $\gtrsim 10^{35}(d/3.5\text{ kpc})^2$ ergs s^{-1} per logarithmic band, and that shifted He II $\lambda 4686$ will be at least three orders of magnitude down from shifted Hα. The minimum energy of the compact radio source is compatible with its lying along the beams: the interaction of the beams with the ambient medium would naturally produce particle acceleration. We therefore suggest that the beams may be resolvable by VLBI at $\sim 10^{-1}$ arcsec resolution and will be found to precess with a 164 day period about the long axis of W50. Finally, we point out the need for VLA and high-sensitivity aperture synthesis observations of SS 433/W50, which may reveal beam structure on a variety of scales. Our model predicts that the central regions, $r \lesssim 10^{16}$ cm, may not be resolved at $\lambda \gtrsim 10$ cm due to the free-free opacity of the proposed ambient medium. W50 may eventually be detectable as a weak ($\lesssim 10^{34}$ ergs s^{-1}) hard X-ray

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source, with faint optical filaments at a pressure exceeding 2×10^{-10} dyn cm^{-2}.

Because of the short total lifetime ($\lesssim 10^5$ years) of SS 433 and its rather unusual evolutionary history in our models, objects of this type should be rare. However, other rapidly rotating neutron stars embedded in opaque gaseous envelopes could exist. They might produce winds or beams as described in § V. Without close companions, the beams would not precess and might not emit lines efficiently. However, the beams would interact with the interstellar medium, producing filled-in SNRs with two oppositely directed extensions. Thus, other SS 433 objects might be detected as compact ratio sources within SNRs similar in morphology to W50. If the wind were uncollimated, then the SNR would have a more spherically symmetric appearance, and the photosphere of the wind might be visible as a very hot, X-ray/UV star.

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REFERENCES

Abell, G. O., and Margon, B. 1979, *Nature*, **279**, 701.
Arons, J. 1979, *Proc. Chapman Conf. on Magnetospheric Boundary Layers*, in press.
Bardeen, J. M., and Petterson, J. A. 1974, *Ap. J. (Letters)*, **195**, L65.
Baym, G., Pethick, C., Pines, D., and Ruderman, M. 1969, *Nature*, **224**, 872.
Blandford, R. D., and McKee, C. F. 1976, *Phys. Fluids*, **19**, 1130.
Blandford, R. D., and Rees, M. J. 1974, *M.N.R.A.S.*, **169**, 395.
Blandford, R. D., and Znajek, R. L. 1977, *M.N.R.A.S.*, **179**, 433.
Clark, D. H., and Murdin, P. 1978, *Nature*, **276**, 44.
Crampton, D., Cowley, A. P., and Hutchings, J. B. 1979, *IAU Circ.*, No. 3388.
Cruddace, R., Paresce, F., Bowyer, S., and Lampton, M. 1974, *Ap. J.*, **187**, 497.
Daltabuit, E., MacAlpine, G. M., and Cox, D. P. 1978, *Ap. J.*, **219**, 372.
Davidson, K., and Ostriker, J. P. 1973, *Ap. J.*, **179**, 585.
de Sitter, W. 1916, *M.N.R.A.S.*, **77**, 155.
Fabian, A. C., and Rees, M. J. 1979, *M.N.R.A.S.*, **187**, 13P.
Hatchett, S., Buff, J., and McCray, R. 1976, *Ap. J.*, **206**, 847.
Illarionov, A. F., and Sunyaev, R. A. 1975, *Astr. Ap.*, **39**, 185.
Katz, J. I. 1979, preprint.
Liebert, J., Angel, J. R. P., Hege, E. K., Martin, P. G., and Blair, W. P. 1979, *Nature*, **279**, 384.
MacAlpine, G. M. 1976, *Ap. J.*, **204**, 694.
Margon, B., Ford, H. C., Grandi, S., and Stone, R. P. S. 1979*a*, *Ap. J. (Letters)*, **233**, L63.
Margon, B., Ford, H. C., Katz, J. I., Kwitter, K. B., Ulrich, R. K., Stone, R. P. S., and Klemola, A. 1979*b*, *Ap. J. (Letters)*, **230**, L41.
Marshall, F. E., Swank, J. J., Boldt, P. J., Holt, S. S., and Serlemitsos, P. J. 1979, *Ap. J. (Letters)*, **230**, L145.
Martin, P. G., Murdin, P. J., and Clark, D. H. 1979, *IAU Circ.*, No. 3358.
Martin, P. G., and Rees, M. J. 1979, *M.N.R.A.S.*, in press.
McKee, C. F., and Cowie, L. L. 1977, *Ap. J.*, **215**, 213.
Mestel, L. 1968, *M.N.R.A.S.*, **138**, 359.
Milgrom, M. 1979, *Astr. Ap.*, **76**, L3.
Misner, C. W., Thorne, K. S., and Wheeler, J. A. 1973, *Gravitation* (San Francisco: Freeman), p. 1119.
Netzer, H. 1978, *Ap. J.*, **219**, 822.
Paczyński, B., and Wiita, P. 1979, in press.
Ryle, N., Caswell, J. L., Hine, G., and Shakeshaft, J. 1978, *Nature*, **276**, 571.
Ruderman, M. 1972, *Ann. Rev. Astr. Ap.*, **10**, 456.
Seward, F. D., Page, C. G., Turner, N. J. L., and Pounds, K. A. 1976, *M.N.R.A.S.*, **175**, 13P.
Shull, J. M., and McKee, C. F. 1979, *Ap. J.*, **227**, 131.
Stephenson, C. B., and Sanduleak, N. 1977, *Ap. J. Suppl.*, **33**, 459.
Tarter, C. B., and Salpeter, E. E. 1969, *Ap. J.*, **156**, 953
Tucker, W. H., and Koren, M. 1971, *Ap. J.*, **168**, 283.
Velusamy, T., and Kundu, M. R. 1974, *Astr. Ap.*, **32**, 375.

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