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Relativistic Jets in SS 433

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Summary. A variety of recent optical, radio, and x-ray observations have confirmed the hypothesis that the peculiar star SS 433 is ejecting two narrow, opposed, highly collimated jets of matter at one-quarter the speed of light. This unique behavior is probably driven by mass exchange between a relatively normal star and a compact companion, either a neutron star or a black hole. However, numerous details regarding the energetics, radiation, acceleration, and collimation of the jets remain to be understood. This phenomenon may well be a miniature example of similar collimated ejection of gas by active extragalactic objects such as quasars and radio galaxies.

It has been remarked (*1*) that SS 433 is the star that made its catalog famous. While this statement is an injustice to the objective prism spectroscopists whose patient work helped lead to the discovery of this and many other unusual objects, it does nicely illustrate the surprise with which this most unusual 14th magnitude star emerged into the scrutiny of the astronomical community. Discovered as a strong source of Hα emission on objective prism plates taken 20 years ago (*2*), the object resurfaced in 1978, when three independent groups called attention to its unusual properties. Seaquist *et al.* (*3*) and Ryle *et al.* (*4*) noted that it is an intense source of radio emission located near the center of the extended, radio-emitting supernova remnant W50, while Clark and Murdin (*5*) suggested it as the optical counterpart of both this radio source and a previously known variable x-ray source, A1909+04 (*6*).

The most unusual characteristics of SS 433 emerged shortly thereafter, when a series of optical spectra (*7*) showed intense, broad optical emission lines whose profiles and, most surprisingly, wavelengths changed drastically from night to night. One can see from Fig. 1, among the first spectra we obtained, that this is hardly a subtle effect. Although we initially resisted the most simple interpretation of such strong features as Doppler-shifted Balmer and He I lines, further observations of spectra with multiple lines all sharing the same redshift, and a different set of (also multiple) features with identical blueshifts, rapidly made all other interpretations of the "moving" spectral features untenable (*8*). Figure 2 provides a particularly vivid example of these data. The amplitudes of the Doppler shifts of these emission lines are unprecedented, corresponding to velocities up to 50,000 kilometers per second for the redshift and 30,000 km/sec for the blueshift, but yet another surprise emerged from this first year of observations: the modulation of the Doppler shifts is cyclic (*8*), with a period of approximately 164 days.

Interpretation of the Variable Doppler Shift

The earliest theoretical attempts at interpreting these phenomena turned out to be remarkably close to the still-current models. Fabian and Rees (*9*) pointed out that narrowly collimated, colinear beams ejected in opposite directions from a central object could explain some facets of the data. Independently, Milgrom (*10*), without knowledge of the 164-day spectroscopic period [which was first announced (*11*) before the appearance of his manuscript], went even further to speculate that the velocity variations of the emission might be periodic, caused by a cyclic rotation of the beam axis inclined to the line of sight. Abell and Margon (*12*), who had the benefit of an extended series of spectroscopic observations generously contributed by many different University of California observers (*13*), were able to confirm and considerably elaborate Milgrom's suggestion, and solve for the values of the free parameters of what has come to be called the kinematic model of SS 433.

The current status of the kinematic model is summarized in Fig. 3 [see also (*14*)]. Here we see data extending over almost three complete years, from June 1978 through April 1981. There are almost 500 individual values of redshifts and blueshifts of the SS 433 emission lines in this data base, gathered on 292 separate nights. A simple nonlinear least-squares fit to the kinematic model yields free parameter values listed in (*15*), and the best-fit model with these parameters is also displayed in Fig. 3. Additional spectroscopic observations have been presented (*16–18*) and are in agreement with the more extended data discussed here.

From the data in (*15*), we note that the systemic ejection velocity of the material emitting the spectral lines is $0.26c$, where c is the speed of light, and the two inclination angles in the system (the rotation axis to the plane of the sky, and the ejection axis to the rotation axis) are 79° and 20°. The optical data alone cannot distinguish which angle is which, and indeed the ambiguity of the model goes much deeper than this: a wide variety of different physical models (infalling jets, expelled jets, disks illuminated by rotating beams) are potentially compatible with the spectroscopic data. As we shall see shortly, more recent radio observations have neatly resolved these ambigu-

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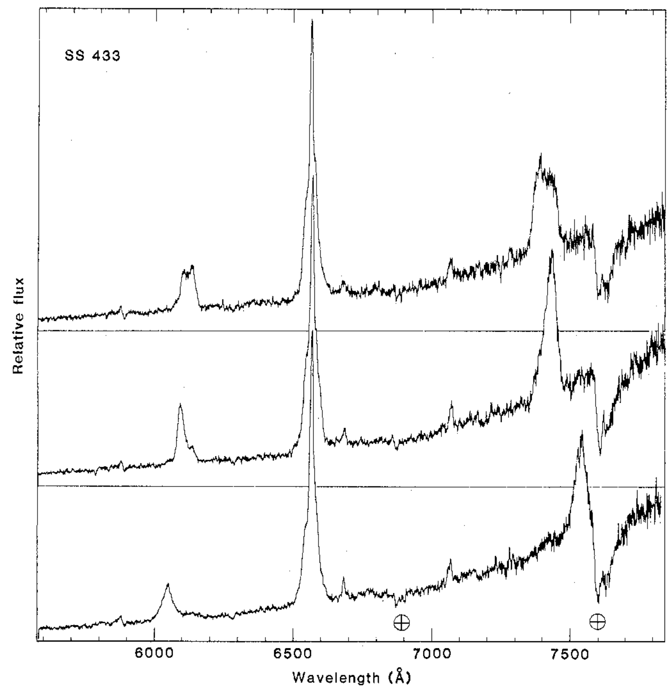

Fig. 1. Spectra of SS 433 obtained on three of four consecutive nights in October 1978, using the Lick Observatory 0.6-meter reflector, with a spectral resolution of approximately 10 Å. The dramatic changes in the profiles and wavelengths of the Doppler-shifted Hα emission features near 6100 and 7400 Å are readily apparent. Telluric absorption bands are also indicated, and weak stellar emission at He I 5876, 6678, and 7065 Å can also be seen. [Adapted from Margon *et al.* (*7*)]

ities, and give us confidence not only that the kinematic model is correct but that the ejected twin jet picture is the proper physical description of the system.

It is gratifying that such a simple model fits the enormous velocity variation (80,000 km/sec) so nicely. On the other hand, it is clear from Fig. 3 that, at least in a statistical sense, the kinematic model is a terrible overall fit to the entire data base. The accuracy of an individual Doppler shift determination is typically better than 500 km/sec, and is limited not by the resolution of the observations but rather by the ambiguity in measuring the center of the broad, irregular spectral features. Yet the root-mean-square residual of the least-squares fit to the data (*15*) is 3000 km/sec, far in excess of this worst-case measurement error. Clearly there must be additional physical effects yet to be described which grossly influence the radial velocities, at a level of approximately 10 percent of the sinusoidal variation. We find that a stochastic jitter of the beam direction of very modest amplitude nicely describes this excess scatter. The beam opening angle is inferred to be of the order of a few degrees, from the ratio of the moving line width to the beam systemic velocity. A jitter in the beam pointing direction of this same angular scale will reproduce the observed scatter amplitude in the radial velocities quite well. To reverse the problem, it would be quite surprising if the mechanism which "aims" this beam of velocity 0.26*c* also has an accuracy greatly in excess of the beam width; in retrospect, deviations of the observed amplitude are perhaps expected. Thus this hypothesized jitter in the pointing direction is a consistent, although not unique, explanation of the large observed deviations from the most simple kinematic model. Periodic small-amplitude deviations have also been proposed (*19*).

It is straightforward to argue (*12, 20*) that, because the inferred kinetic energy in the ejected beam model grossly exceeds the rotational energy stored in a compact star, the 164-day clock in SS 433 is unlikely to be simple rotation. Most authors [for instance, Katz (*21*)] have therefore considered precession as the most likely mechanism for rotating the jet axis; then, of course, a mechanism to drive this precession is needed. One is thus led naturally to suspect that SS 433 is a member of a close binary system. One arrives at the same inference by noting that the total kinetic energy dissipated by SS 433 ($\gtrsim 10^{38}$ ergs per second) is not dissimilar to the radiated x-ray luminosity of the more luminous x-ray binary systems; for some reason SS 433 converts its accretional energy to kinetic form rather than radiation (*22*). Firm evidence for this companion emerged (*23*) through the discovery of a 13-day small-amplitude spectroscopic variation in the "stationary" Balmer and helium emission lines—that is, those lines at their laboratory wavelengths in the spectrum. The velocity curve suggests a mass ratio of the two stars near unity, and thus, in the picture where the compact star is a neutron star, implies a main sequence star of spectral type near F as the companion. Such an object would be too subluminous to be detected directly in the spectrum, but for reasonable parameters one expects photometric eclipses of the luminous disk (in this picture responsible for the stationary emission lines and most of the continuum) by the dark companion (*24*).

Further Observations

In a reversal of the normal order of observations of peculiar stars, spectroscopic studies of SS 433 preceded photometric work on the system. However, extensive photometric studies of this variable object, now also termed V1343 Aquilae, are now becoming available (*25*). There is a general agreement that the V band magnitude of the object varies on time scales of days and months by up to one magnitude, but that any color variations are considerably less extreme. This amplitude of variability seems too large to be entirely due to the "moving" spectral lines passing in and out of the photometric band passes (although a nonnegligible portion of the observed variability must be due to this), and therefore the evidence seems firm that the continuum does indeed vary. However, the situation regarding periodicities in this variation is at the moment more uncertain. All of the groups (*25*) present evidence for a periodic variation with a time scale similar to, but significantly different from, half of the 13-day spectroscopic period. Whether this discrepancy is profound is not yet certain. In addition, the Soviet and Israeli groups have presented evidence for a 164-day photometric variation from both historical and modern plate material. If this can be confirmed it will be especially interesting, as it will be the best evidence that the 164-day period cannot be changing on a long time scale. In contrast, the moving spectral lines do show evidence for short-term instability in this period (*26*).

One may conservatively conclude from the current photometric results that deep eclipses with a 13-day period are absent. We are then confronted with an apparent incompatibility with the 13-day spectroscopic data, but a variety of resolutions are available. The system may have a high and inverted mass ratio (*24*) like WZ Sagittae, or the binary orbital plane may be misaligned with the symmetry plane of the precession (making the true orbital inclination of the system indeterminate and not necessarily equal to the inclination angle determined from the kinematic model). More recent spectroscopic data (*27*) on the 13-day period yield an amplitude and phase significantly different from the original estimates (*23*) and, if confirmed, may suggest the presence of a more massive normal star. Regardless of the luminosity of the primary, it is uncertain whether this star is visible in the SS 433 optical spectrum, as has been suggested (*17, 28*), simply because the observed spectrum does not resemble that of any type of star. For example, accompanying the broad Balmer and He I emission lines are extremely strong Fe II and O I absorption lines (at 5169 and 7773 angstroms, respectively), and the Fe II strengths are modulated with the 164-day period. This suggests that the entire stationary spectrum originates from the accretion disk.

Recent observations of the linear polarization of SS 433 suggest interesting behavior. The object is polarized a few percent (*29*), but until recently an interstellar origin for this could not be ruled out. However, the polarization proves to be variable in amplitude, and this variation may be synchronized with the 164-day period (*30*). This may imply that a significant component of the optical continuum is nonthermal in origin, consistent with the conclusion above that the spectrum is not that of the primary star.

X-ray observations (*31*) of SS 433 from the Einstein Observatory have provided us with important additional clues to the nature of SS 433. Approximately 90 percent of the x-ray flux from the region is contained in an unresolved point source coincident with the optical position of SS 433 but, perhaps more interesting, the remaining 10 percent originates from two collimated, colinear jets that originate at SS 433 and extend for 0.5° quite accurately aligned with the major axis of the radio emission from W50 [see the map given in (*32*)]. The x-ray data are displayed in Fig. 4. These data provide confirmation of arguments (*20*) that the evolution of W50 has been profoundly influenced by the ejected beams; the radio object, in fact, may not be a supernova remnant at all. Any remaining doubts concerning the association of SS 433 and W50 are also removed by these data—an important point, as most of the remaining radio sources postulated by Ryle *et al.* (*4*) to be analogs of SS 433 have been shown to be chance background superpositions on supernova remnants (*33*). Finally, the length of the observed x-ray jets and a knowledge of the ejection speed from the kinematic data give us a firm lower limit of 10^3 years on the lifetime of SS 433 in its current stage. This number is difficult to estimate by any other technique, especially as we lack any analogous objects. It would be very interesting to learn of any 13- or 164-day modulation of the x-ray flux from the point source, but these data may be beyond the capability of post-Einstein experiments.

Variable Radio Structure

Perhaps the most exciting recent developments in observations of SS 433 have emerged from radio observations. The source shows extended structure, with the major axis of this extension aligned with the long axis of W50 and the x-ray jets, and this structure persists over a wide range of wavelengths and spatial scales. The structure has been studied on scales of a few arc seconds by Spencer (*34*), Hjellming and Johnston (*35*), and Gilmore *et al.* (*36*); at 0.1 arc second by Niell *et al.* (*37*); and at the 10 milliarc second level by Schilizzi *et al.* (*38*). Most of this work has been done at 2 and 6 centimeters, although the extension is detected to frequencies as low as 408 megahertz. All observers with long time baselines (months) find that the spatial structure changes with time, in a manner which gives us some confidence that we are directly observing the effects of the 164-day precession of ejected jets on the surrounding ambient medium.

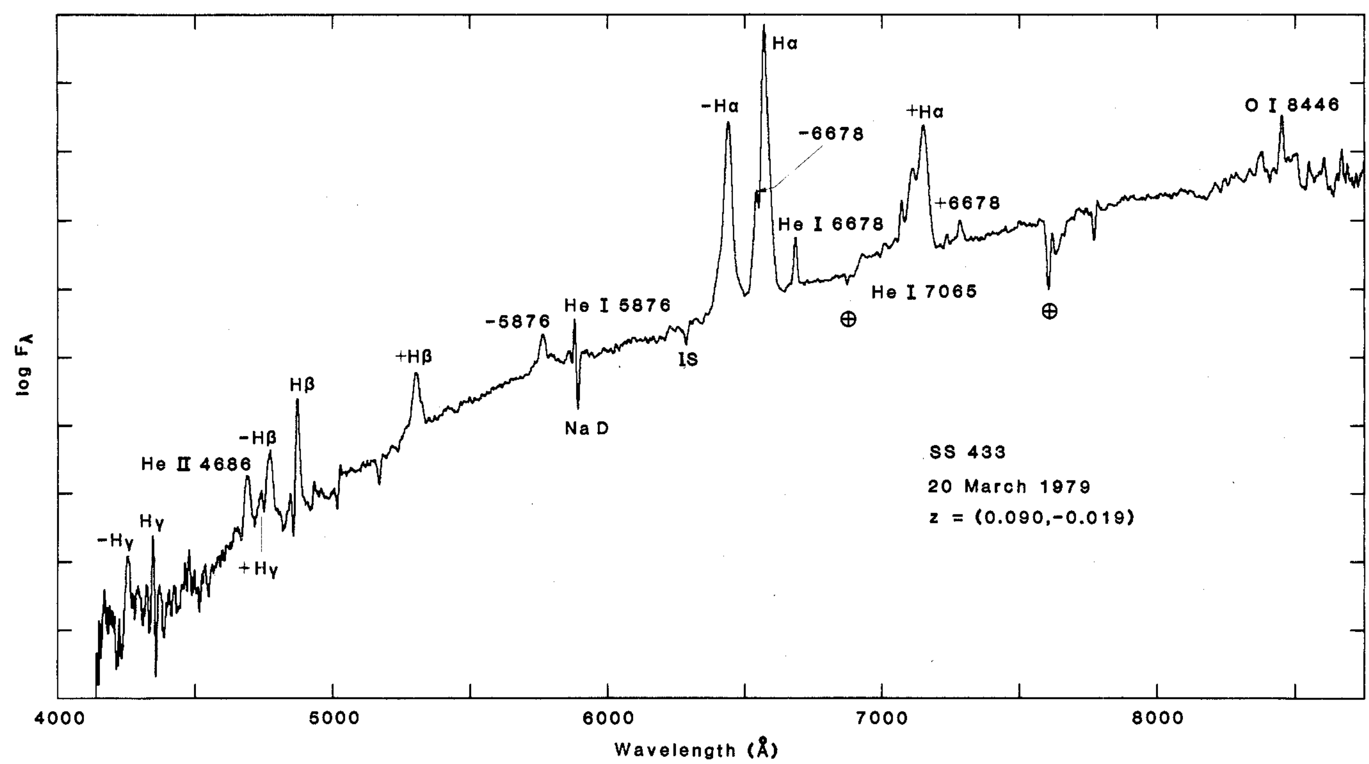

Fig. 2. Spectrum of SS 433 on 20 March 1979, when the pattern of multiple red- and blueshifted emission lines was particularly obvious. Emission lines prefixed with a "plus" are redshifted features, and the "minus" prefix denotes blueshifted features. This spectrum was obtained with the Lick 3-m Shane reflector. Note the very strong stellar absorptions of Fe II 5169 Å and O I 7773 Å, as well as P-Cygni absorption components to the Balmer and He I lines in the "stationary" spectral line system. Each division on the ordinate is 0.83 magnitude. [Adapted from Margon *et al.* (*8*)]

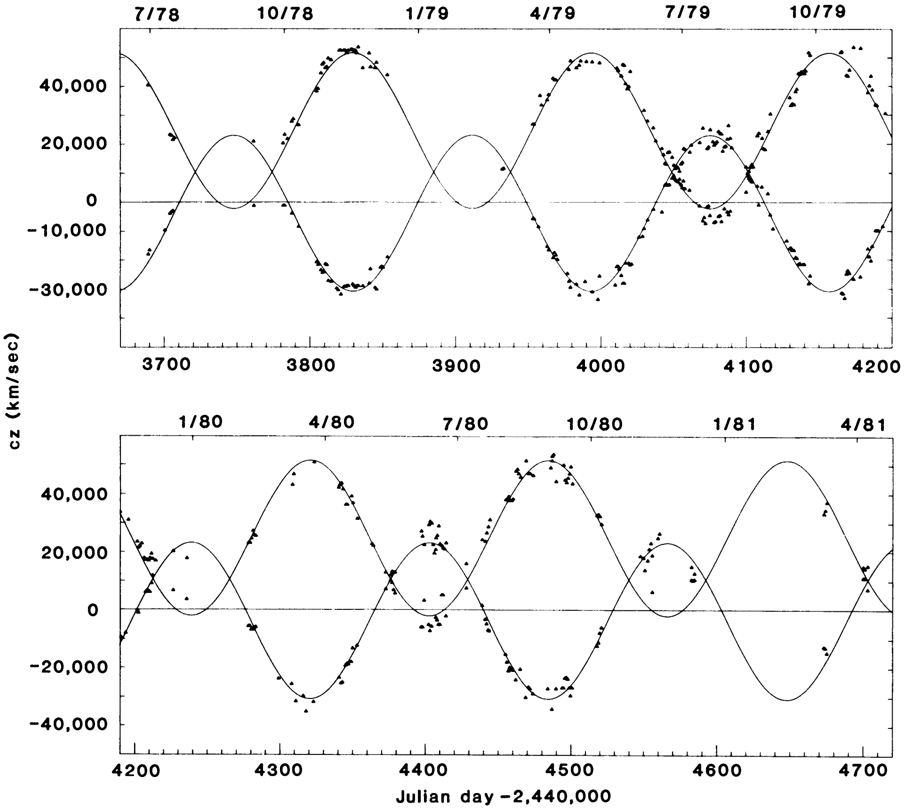

Fig. 3. Values of red- and blueshifts of SS 433 over an almost 3-year period; displayed are 500 separate Doppler-shift values obtained on 300 separate nights. Most of the data were obtained by the author and University of California colleagues, although a few points are from the literature [cited in (*14*)]. The solid line is the best fit to the simple kinematic model (*12*) with free parameter values given in (*15*). The large, constant value of the symmetry axis of the velocities (12,000 km/sec) is due to special relativistic time dilation, a 4 percent effect at velocity $v = 0.26c$.

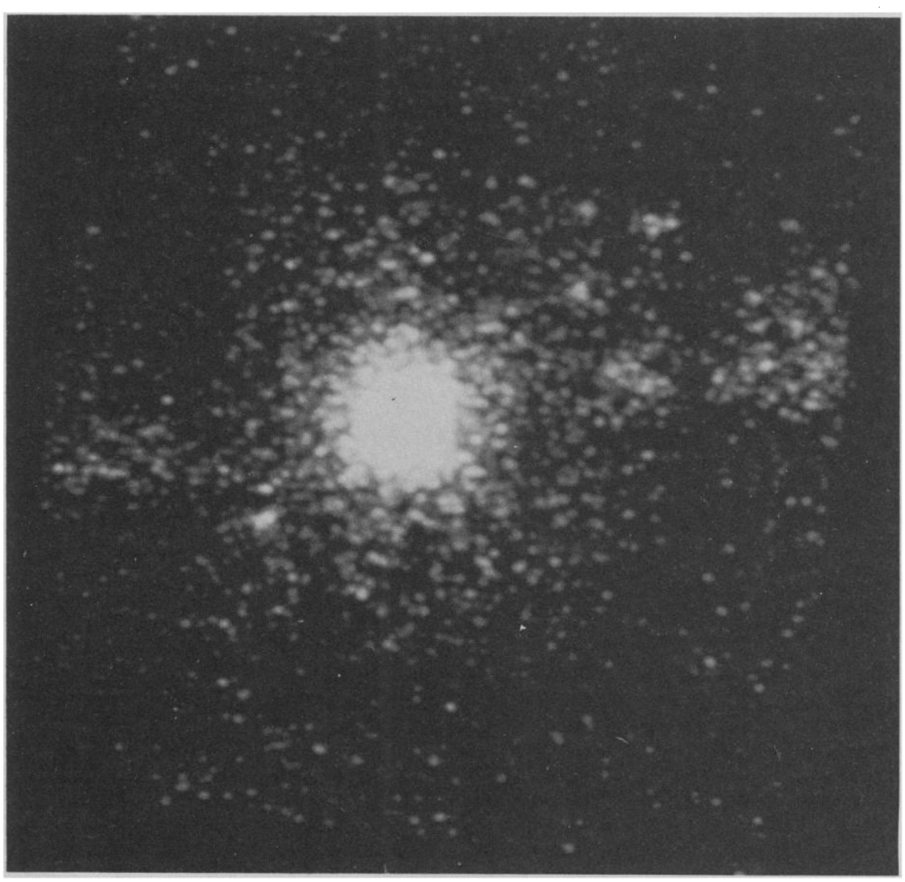

Fig. 4. X-ray image of SS 433, obtained by the Einstein Observatory imaging proportional counter, in the range 0.5 to 4 kiloelectron volts. The 10 percent of the flux located in the collimated, opposing jets is readily apparent, and this axis accurately matches that of the extended radio source W50. [Adapted from Seward *et al.* (*31*)]

Figure 5 shows an example of this time-variable structure from the work of Hjellming and Johnston (*35*). Although these maps at first glance may appear to reveal highly complex structure and chaotic changes therein, a quite simple, quantitative interpretation of these data is available. The locus of the precessing jets in three dimensions can be algebraically "unfolded" and mapped onto the two-dimensional celestial sphere, using the jet ephemeris from optical observations of the moving lines. The resulting pattern is a corkscrew-like shape that agrees astonishingly well with the major features of the radio maps.

One can reverse this procedure (*35*) and derive values for the kinematic parameters from the radio observations, entirely independent of the optical spectroscopy. One can say at the moment that the values so derived are entirely consistent with the optical observations; as the time baseline of the radio observations increases, there is no obvious reason that the radio kinematic parameters cannot equal the optical data in quality. Indeed, the radio emitting regions may be free of the small-scale jitter which profoundly affects the optical radial velocity data, and potentially may therefore yield more accurate kinematic solutions.

These radio data are already vitally important to our picture of SS 433 for several reasons. The most basic is that they unambiguously point to the ejected twin-jet model as the correct interpretation of the kinematic data, an interpretation that is consistent with but not demanded by the optical data. In the case of the radio data, we are actually observing the locus of the ejected blobs as they coast ballistically away from the central source. Thus more exotic models for SS 433—involving, for example, rings and disks around massive black holes—are almost surely ruled out. A second important consequence of the radio observations is that they resolve certain ambiguities from the optical kinematic solution, and go further to calculate parameters that are unavailable from the spectroscopy. The ambiguity between the two inclination angles is removed in the radio kinematic solution; only the 79° angle for the precession plane can be made to fit the data. Furthermore, the radio emitting volume is large enough that we know light travel times are important, while the optical emitting region is small enough that light travel delays cannot be observed. The maps obtained with the Very Large Array (VLA) show significant flux several arc seconds away from the core, corresponding to 10^{17} cm at the source, while the optical emitting region must be equal to or less than 1 light-day (10^{15} cm) or the moving spectral lines would be badly smeared. Therefore, light travel delays must be included in the radio kinematic solution to obtain consistent results. This adds the third dimension to an observation of proper motion of the coasting blobs, and therefore allows the distance to SS 433 to be explicitly calculated. The resulting initial estimates of 5.1 kiloparsecs (*35*) agree well with far more indirect and uncertain estimates from optical observations, which earlier (*7*) had set lower limits to the distance of 3.5 kpc. Finally, one can even infer that the sense of the beam rotation is clockwise (left-handed) from the VLA data.

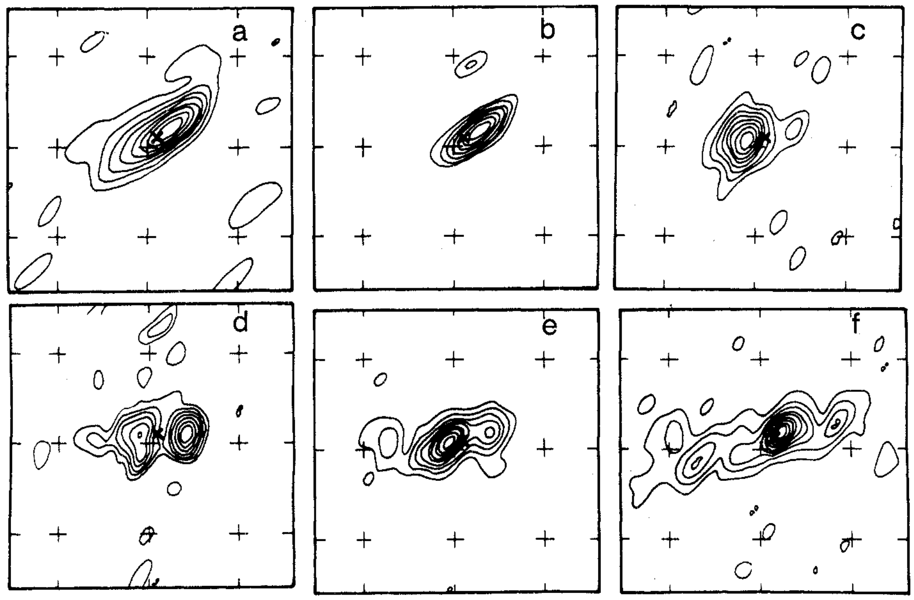

Fig. 5. Maps of SS 433 obtained with the Very Large Array at 4885 MHz over a 9-month period. The linearly polarized intensity contours are at 10 percent levels starting with 90 percent, and the grid of crosses denotes intervals of 2 arc seconds. Maps (a) through (f) were made on 8 to 9 September, 16 September, and 7 December 1979 and 7 March, 5 April, and 20 June 1980, respectively. Spatial changes during these one and a half precession periods of the jet are obvious. [Adapted from Hjellming and Johnston (*35*)]

Theoretical Difficulties

The combination of the optical and radio observations of SS 433 described above leaves us with an accurate measure of the kinematics of the system, and some confidence that we understand what these kinematic equations are describing: the ejection of matter through two collimated, opposing jets. Unfortunately, the specific physical processes associated with this ejection are considerably more poorly understood than the kinematics. Some general physical arguments regarding conditions in the jets (*20, 21, 39*) and reviews listing much of the current theoretical work (*1, 40*) appear elsewhere. An attempt to enumerate the theoretical difficulties might proceed as follows:

1) The data contain no obvious signature of the source of the beam's kinetic energy, although, as discussed above, accretion seems the most attractive choice, by analogy to the x-ray binaries.

2) The details of the acceleration mechanism have yet to be worked out, although Milgrom (*41*) has pointed out that line-locking due to radiative absorptions in the sub-Lyman continuum would yield exactly the observed velocity of $0.26c$.

3) The collimation mechanism has yet to be worked out in detail, although presumably the accretion disk plays an important role [for example, see (*21*)].

4) The nature of the 164-day clock has yet to be defined. As discussed above, most workers opt for precession, but whether general relativistic effects are important and what body drives the precession are not at all clear (*20, 21, 42*).

5) The physical conditions in the optically radiating volume are obscure. Simple recombination seems appealing to explain the moving line spectrum, but selective mechanisms have also been considered. Does the continuum originate from the accretion disk or the companion star?

6) What is the nature of the compact star? Many models have little preference for a 1 $M_\odot$ neutron star over a 1 $M_\odot$ black hole ($M_\odot$ = mass of the sun), although the analogy to x-ray binaries plus conservatism probably favors the neutron star.

7) What is the nature of the companion star? The simplest interpretation of the 13-day spectroscopic curve, a system with mass ratio unity, has problems, and more massive companions may have to be considered.

8) The evolutionary status of SS 433 is grossly uncertain. The lifetime of the phenomenon is probably quite short, $\lesssim 10^4$ years due to the large (but uncertain) mass loss rate alone, but whether this behavior is a precursor to some, most, or all traditional x-ray binaries is not obvious. Observation of even one additional such object would help greatly to clarify this point, but at the moment such an analog eludes us, and there is no strong reason to believe (*33*) that any of the recently suggested candidates are, in fact, similar to SS 433.

Many authors [for example, see (*43*)] have noted that the narrowly collimated, twin-jet structure of SS 433 is familiar to astronomers in the context of an entirely different problem. Active extragalactic nuclei such as quasi-stellar objects and radio galaxies commonly show this twin-lobed structure in their radio emission, stretching over linear scales 10^3 times larger than the x-ray jets of SS 433 and 10^6 times larger than the radio jets. Despite the gross discrepancy in scale, there are good reasons to believe that the same physical mechanisms apply in both cases (*44*). Thus SS 433 may represent a readily accessible small-scale model of these extraordinary extragalactic events and allow detailed observation of the expulsion process.

Although the length of the above list of unanswered questions may seem disheartening, there can be little argument that our understanding of SS 433 has progressed enormously in the 3 years during which the object has been under study. We have gone from a star that is "coming and going at the same time," as described by the popular press, to an enormous set of microscopic observations, at both optical and radio wavelengths, of this most unusual astronomical phenomenon.

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45. The author's work on SS 433 is an ongoing collaboration with S. A. Grandi and R. A. Downes of the University of California, Los Angeles, and S. F. Anderson of the University of Washington. Financial support for this work has been provided by the National Science Foundation (grant AST 77-27745) and the Alfred P. Sloan Foundation. This article is based on a chapter in a forthcoming book, *Accretion Driven Stellar X-ray Sources*, W. H. G. Lewin and E. P. J. van den Heuvel, Eds. (Cambridge Univ. Press, Cambridge, in press).

Human Cell Hybrids: Analysis of Transformation and Tumorigenicity

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In what would now be accepted as a farsighted hypothesis, Theodor Boveri (*1*) proposed that neoplastic cells, as a consequence of chromosomal imbalance, arise from normal cells. This theory has been refined to involve somatic mutation (*2*) as the precipitating cause of neoplastic transformation. The somatic mutation theory now vies strongly with viral (*3*) and epigenetic (*4*) theories of cancer.

The concept that the transition of a normal cell to a neoplastic one is not a simple one-step mutational event but rather a series of progressive events has gained credence in recent years (*5*, *6*). Genetic analysis of these events has been aided by the utilization of somatic cell hybridization techniques (*7*). Examination of hybrid cells resulting from the fusion of a tumorigenic cell with a normal one should allow the determination of whether tumorigenicity behaves as a dominant or recessive trait. The answer to this seemingly simple question, however, has been the subject of considerable controversy.

Early investigators (*8*) isolated hybrid cells derived from the fusion of mouse cells of low malignant potential with those of high malignant potential. The hybrids were as malignant as the highly malignant parent, thereby leading to the interpretation that tumorigenicity behaves as a dominant trait. However, Harris, Klein, and their colleagues on the basis of an extensive series of experiments came to the opposite conclusion (*9*). Their experiments indicated that, when highly malignant mouse cells were fused with other mouse cells of low malignant potential, the resulting hybrids were transiently suppressed in their ability to form tumors. Tumorigenic segregants, which had regained the malignant potential of the highly malignant parent, arose rapidly from these hybrids. Analyses of the chromosomal complements of the parental and hybrid cell populations indicated that the tumorigenic segregants had lost substantial numbers of chromosomes, including those originating from the normal parent. Similar investigations, using other intraspecific rodent hybrids, have essentially confirmed the findings of Harris *et al.* (*10*), although there are certainly notable exceptions to this generalization (*11*). The major drawback in all of these studies has been the chromosomal instability of intraspecific rodent hybrids, where a significant proportion of the total chromosomal complement is rapidly lost. This rapidity of

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