THE ASTROPHYSICAL JOURNAL, 233:L63–L68, 1979 October 15

ENORMOUS PERIODIC DOPPLER SHIFTS IN SS 433

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Received 1979 June 6; accepted 1979 July 11

ABSTRACT

We have previously reported prominent "moving" emission lines in the visible spectrum of Stephenson-Sanduleak 433, the optical counterpart of a variable radio and X-ray source. Further observations show that despite the implausible velocities and changes in velocities implied if the moving features are interpreted as Doppler-shifted Balmer lines, this explanation is indeed correct. Spectroscopy of SS 433 on 51 nights in 1978–1979 reveals that the unidentified features are two sets of Balmer and He I lines, one with large and changing redshift, and the other with large and changing blueshift. Combining our data with published earlier observations, we obtain Doppler shifts on 80 nights in the period 1978 June to 1979 June. These data indicate that the velocity variations are cyclical, repeating in both the blueshift and redshift systems with a period of 164 ± 3 days. The two systems have thus far been observed to reach maximum positive and negative radial velocities of +50,000 and −35,000 km s^{-1}, respectively, are always symmetric about redshift $z = 0.04$, and follow roughly sinusoidal velocity curves. We discuss in addition a variety of interesting short-term spectroscopic details, including minor but highly significant deviations of the radial velocity from the sinusoid, and nightly line profile changes, sometimes appearing as mirror-image events in the redshift and blueshift systems. The behavior of SS 433 is unprecedented.

Subject headings: radio sources: variable — stars: emission-line — stars: spectrum variables — X-rays: sources

I. INTRODUCTION

The emission-line object Stephenson-Sanduleak 433, first noted on objective prism plates (Stephenson and Sanduleak 1977; Krumenaker 1975), is the optical counterpart of a variable radio source (Clark and Murdin 1978; Ryle *et al.* 1978; Seaquist *et al.* 1979) and also exhibits variable X-ray emission (Seward *et al.* 1976; Forman *et al.* 1978; Marshall *et al.* 1979). We have previously reported observations which show that SS 433 has a most unusual visible spectrum (Margon *et al.* 1979), displaying intense emission lines at unfamiliar wavelengths, in addition to a set of zero-velocity Balmer and He I emissions. Furthermore, these unidentified features were seen to change in wavelength drastically on 1 day time scales. Despite equivalent widths of the moving features comparable to those of the stationary Balmer lines, the simplest explanation of these bizarre features—that of red- and blueshifted Balmer emission due to the Doppler effect—seemed implausible for many reasons. The velocities implied are enormous, up to 50,000 km s^{-1} of redshift and −35,000 km s^{-1} of blueshift. The *changes* in velocity implied are also very large, requiring $\Delta v = 30{,}000$ km s^{-1} in 40 days to explain the observations of 1978. The lines are observed to move in opposite directions, e.g., an infrared feature gained in wavelength while a red feature simultaneously diminished in wavelength. Finally, an identification of the features with Balmer emission would imply a very high velocity yet rather cool ($\sim 10^4$ K) medium, a ratio of $\sim 10^4$ between bulk and thermal ion velocities.

In this *Letter* we present extensive further observations of SS 433 which show unambiguously that, despite the above objections, the moving spectral features are indeed Doppler-shifted Balmer (and He I) emissions, which display unprecedented velocities and changes in velocities. Liebert *et al.* (1979) have independently reached a similar conclusion. In addition, we find the velocity variations to be periodic, confirming a prescient comment by Milgrom (1979).

II. OBSERVATIONS

Our sample of data on SS 433 has been considerably extended since the previous report (Margon *et al.* 1979). We present here spectroscopy obtained on 51 nights in 1978–1979 from the Lick and Kitt Peak Observatories. The Lick data were obtained chiefly with the Robinson-Wampler image-tube scanner at the 3 m Shane or 0.6 m reflectors, at 8–10 Å resolution, generally in the

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green and/or red spectral regions. Three nights of data were obtained in the near-infrared (extending to 1.1 μm) at 10 Å resolution, using the UCLA Reticon scanner (Wood 1979) at the Shane Telescope, and four nights of further scanner data in the green were obtained at the Kitt Peak 4 m Mayall reflector. In all cases, two or more of the previously reported anomalous emission features are visible in these spectra; in many cases, up to eight such lines are detected.

The spectra of SS 433 obtained at the beginning of the 1979 observing season dispel all doubts as to the proper interpretation of the moving emission features. An example of these spectra is shown in Figure 1, which displays data where good signal-to-noise ratio and broad spectral coverage were simultaneously achieved. All of the prominent Balmer and He I emissions are seen to be tripled, with one component approximately at rest, and the second and third components displaced to the red and blue. The breadths and asymmetries of the anomalous displaced lines somewhat limit the accuracy with which the centroids may be determined; velocities measured for these features conservatively yield uncertainties of ± 200 km s^{-1}. We find that the four red-displaced emission components (Hγ, Hβ, Hα, and He I 6678) all have $z = \Delta\lambda/\lambda = 0.090 \pm 0.001$, while the five blue components (Hγ, Hβ, He I 5876, Hα, and He I 6678) all yield $z = -0.019 \pm 0.001$. Redshifted He I 5876 is not seen as it coincides in wavelength with the broad, more intense, blueshifted Hα line. As only the Doppler effect is known to displace spectral lines with constant $\Delta\lambda/\lambda$ and either sign, the identifications of these features seem absolutely secure.

We have examined our spectroscopic data on all other nights, and find that the anomalous emission lines may always be identified as red- or blueshifted Balmer or He I 5876, 6678 features. As the three emission-line systems each contain six to eight strong lines, each typically 100 Å wide, and the two moving systems traverse up to 1000 Å of displacement with opposite sign, confused or overlapping lines are common in our spectra. Amusingly, we obtained a spectrum on 1979 April 5 displaying a nearly Gaussian emission feature at 5550 Å, which proves to consist of nearly equal fractions of redshifted Hβ moving toward longer wavelengths, and blueshifted He I 5876 moving toward shorter wavelengths, coinciding in position on that night to an accuracy of 1%. Superposition or blending of moving and stationary lines is also common. For example, the strange Hβ profile displayed in Figure 2 of Margon *et al.* (1979) is due to near-superposition on that night of rest and blueshifted components of the same line. Such coincidences seem to account entirely for the rapid profile changes noted previously in the rest-system emission lines. The observed equivalent width variations in the rest lines, however, are too large to be attributed to moving features, and must represent genuine variations in the emission and/or continuum strength.

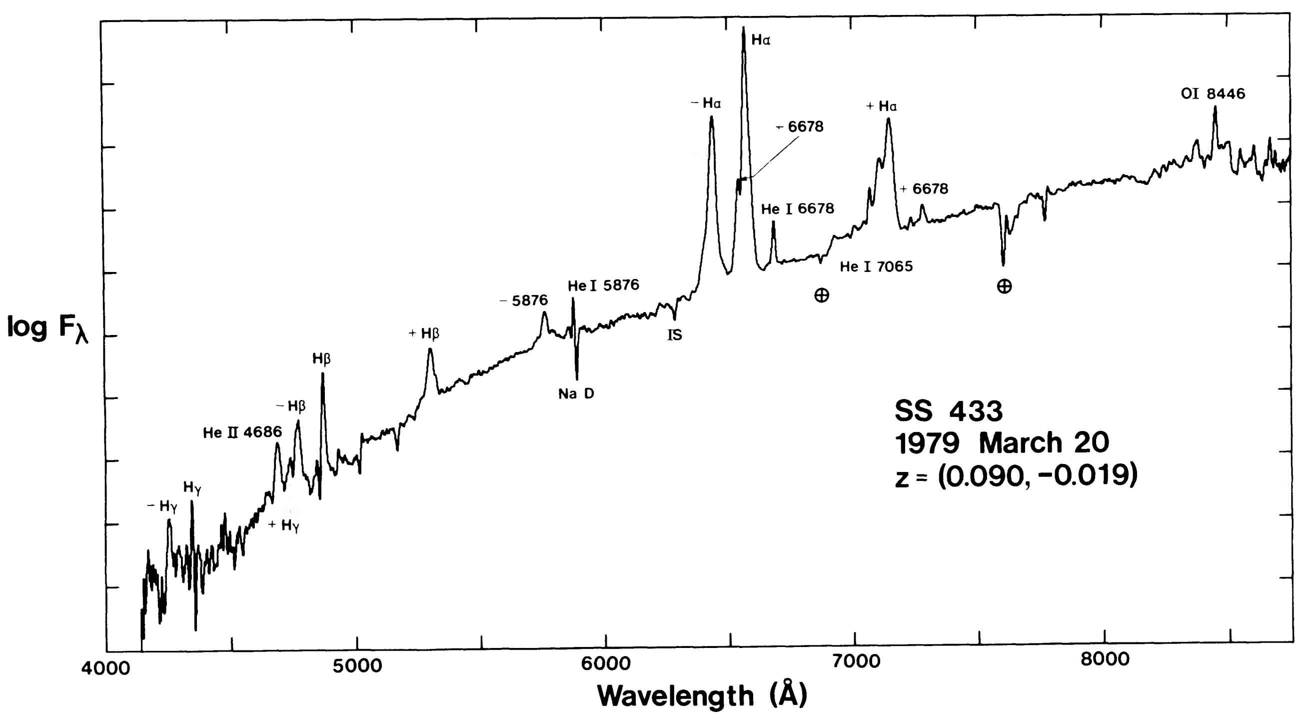

FIG. 1.—Spectrum of SS 433 obtained on 1979 March 20 with the Lick Observatory 3 m Shane reflector. The data have been converted to flux units via observations of spectrophotometric standard stars from the list of Stone (1977). The principal emission features are identified, and the prefixes "+" and "−" to these labels denote lines in the redshift and blueshift systems, respectively. Stronger interstellar and telluric absorption features are also labeled. Each division on the ordinate corresponds to 0.83 mag.

Despite these obstacles to simple interpretation, we are able to easily and unambiguously identify the majority of emission lines on all of our spectra as Doppler-shifted Balmer and He I features. On most nights we obtain a value for the velocity of both the red- and blueshift systems derived from two or more emission lines in each system; occasionally, values for only one of the two Doppler shifts are available due to limited spectral coverage or particularly unfavorable line superpositions. This consistent success in line identifications has led us to confidently reinterpret the observations of SS 433 tabulated by Mammano, Ciatti, and Vittone (1979) on 20 additional nights in 1978 when we have no data. Although these authors attribute the anomalous emission features to Zeeman splitting, the wavelengths presented indicate clearly that their "IR 1 band" and "Red 1 band" are red- and blueshifted Hα, respectively. Liebert *et al.* (1979) provide data for four additional nights where we lack coverage, and Liebert (1979) has kindly communicated a handful of further observations obtained at Steward. Finally, the spectra of Clark and Murdin (1978), as reinterpreted by Martin, Murdin, and Clark (1979), provide two further sets of velocities from 1978 June and July. A total of 80 nights of data, spanning 1978 June through 1979 June, are therefore available at this time.

In Figure 2, we display a plot of the red- and blueshifts derived from this data sample versus time. The measurement uncertainties in the velocities are very small compared with the magnitude of these velocities and smaller than the plotting symbols in the figure. Therefore, the scatter of the data about the smooth curves readily suggested by the eye is genuine and intrinsic to the object. Maximum velocities of +50,000 and −35,000 km s^{-1} were reached by the red- and blueshift systems, respectively, in 1978 November and again in 1979 April. The two moving line systems consistently maintain symmetry about redshift $z = 0.04$, despite the fact that the systemic velocity of SS 433 as measured by the rest emission-line system is small. This has previously been noted by Milgrom (1979) on the basis of a small fraction of our data sample.

There are fascinating episodes of departure of the velocity curve from the smooth trend, which appear as correlated events in the two separate systems and are very different from the general scatter. The best example occurs near the end of 1978 October, and is readily

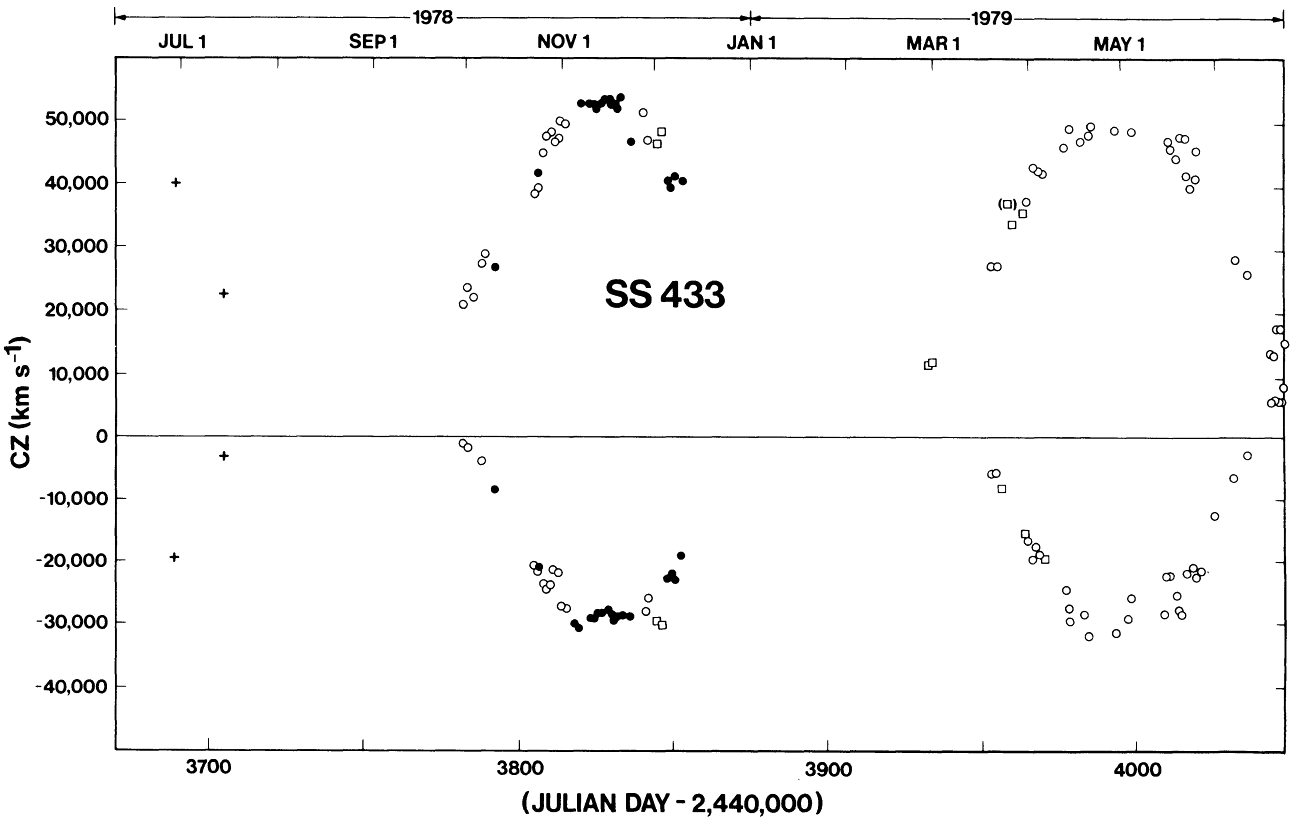

FIG. 2.—Values of the red- and blueshift of emission lines in SS 433 versus time. *Open circles*, present work; *filled circles*, reinterpretation of data from Mammano *et al.* (1979); *squares*, Liebert *et al.* (1979) and Liebert (1979); *crosses*, Clark and Murdin (1978) and Martin *et al.* (1979). Note that although the ordinate displays the Doppler shifts in velocity units *cz*, in conformity with traditional radial velocity spectroscopy, the actual kinematic velocity values are somewhat different due to the significant Lorentz factor.

apparent in Figure 2. The blueshift system abruptly stopped its smooth decrease in velocity, and in a span of three nights reversed sign and gained velocity, to a point 5000 km s^{-1} disjoint from the previously smoothly changing curve. Then in a rapid time (equal to or faster than our resolution of 1 day), the system jumped back to a blueshift completely consistent with the previous extrapolation, and resumed its smooth decrease in velocity. Simultaneously with this event, the redshift system executed a correlated but mirror-image diversion from its smooth curve, losing approximately 2500 km s^{-1} with respect to a smooth extrapolation of previous data, and then regaining the "expected" velocity in a short time. To within our time resolution, the events are simultaneous in the red- and blueshift lines. Similar events occurred near 1978 December 3 and 1979 May 18. The emission-line profiles show no dramatic changes during these events, and so profile variation is not responsible for this phenomenon.

Our data contain other interesting examples of mirror-image correlations between the redshift and blueshift systems, not only in velocity behavior, but also in emission-line profiles. The profiles, while often variable night to night and quite asymmetric, are sometimes remarkable mirror images of each other (also noted from our data by Amitai-Milchgrub, Piran, and Shaham 1979; Terlevich and Pringle 1979). A good example appears in Figure 3 of Margon *et al.* (1979), and we have observed many other such episodes. However, we stress that we have an equally large number of observations where such symmetry seems definitely absent. Furthermore, the sense of the line-profile asymmetry is not constant. Many of the moving emission profiles have noticeably steeper edges on the side with larger Doppler shift, perhaps suggesting rapid expansion into a confining exterior medium. However, we have also observed contrary examples in both systems.

Some of our more recent spectra extend considerably redward of our previously reported data. In addition to several Paschen lines, the most interesting new emission features we see are O I 8446, He II 10,124, and He I 10,830 in the rest system. These lines appear strongly on all of our spectra with appropriate coverage, and the O I line has been previously reported by Mammano, Ciatti, and Vittone (1979). The strength of this feature, which also appears in novae, symbiotic stars, and Seyfert nuclei, suggests that it is almost surely due to a Bowen-like Lβ fluorescence mechanism (Grandi 1975; Strittmatter *et al.* 1977). The spectra occasionally show a few quite strong (up to 20 Å equivalent width) but highly variable emission lines in the rest system, with no obvious identifications. Among these are the 5810 Å feature mentioned by Liebert *et al.* (1979). We have also searched the moving line systems carefully for higher excitation features, and find no strong evidence for such emission.

Finally, our data definitely indicate a secular trend in the strengths of the moving emission-line systems. In Figure 1 it can be seen that the red- and blueshifted emission lines have roughly comparable equivalent widths. By late 1979 April, however, the intensities of the redshifted lines decreased sharply, and the redshift system in 1979 May had line strengths very substantially weaker than the blueshift system, and also far weaker than when the redshifts last had comparable velocity, in 1978 November. We also see changes in the ratio of He I to Balmer equivalent widths in the moving systems, both on long (months) and short (days) time scales.

III. DISCUSSION

A cursory examination of Figure 2 suggests that the velocity variations of SS 433 are periodic. This indeed appears to be the case when the data are folded with trial periods chosen to approximately superpose the velocities. We have folded the data with a variety of trial periods in the 150–170 day range, and find that 164 ± 3 days provides the best superposition. This value is based on more data than that quoted by Margon (1979), and supersedes that preliminary period estimate.

In Figure 3 we display the folded velocity curve for all available data, assuming a 164 day period. Data from the entire span of almost 1 year superpose with no obvious increase in scatter from the raw data (Fig. 2). As the full amplitude of the velocity variation exceeds 80,000 km s^{-1}, and the data of Figure 3 indicate that the system recovers its velocity over this huge range to an accuracy of $\sim$5% each 164 days, the assumption of periodicity appears strongly supported at this time. Milgrom (1979) predicted a possible period of 4–6 months, again on the basis of a small fraction of our data, and we now verify this prediction. Due to gaps in the data, about 30% of the cycle is as yet unobserved. We currently can set only weak limits on any change of period with time, $\dot{P} \lesssim 10^{-2}$.

The symmetry about $(1 + z) = 1.04$ is again readily apparent in the folded data. It is compelling to interpret this offset as the transverse Doppler effect, almost independent of the geometric model associated with these observations (see also Milgrom 1979). A gravitational redshift and even a cosmological (Hubble) component could also contribute to this offset, and physical rather than kinematic arguments must be invoked to rule out these possibilities. If the entire offset *is* due to the transverse Doppler effect, as seems likely (Abell and Margon 1979; Katz 1979), then it is easy to demonstrate that the observed value of the line of symmetry, $(1 + z_{\rm sym})$, is simply identical to γ, the Lorentz factor. The data are then compatible with a single fundamental system velocity of ±81,000 km s^{-1}, modulated with a 164 day cosine function, and appropriately inclined to the line of sight. The surprisingly small scatter in Figure 3 indicates that the two moving line systems are accurately matched in velocity, and maintain this value over extended periods of time. A complete kinematic model compatible with these data has been described by Abell and Margon (1979).

As Figure 3 bears a cursory resemblance to the velocity curve of a double-lined spectroscopic binary,

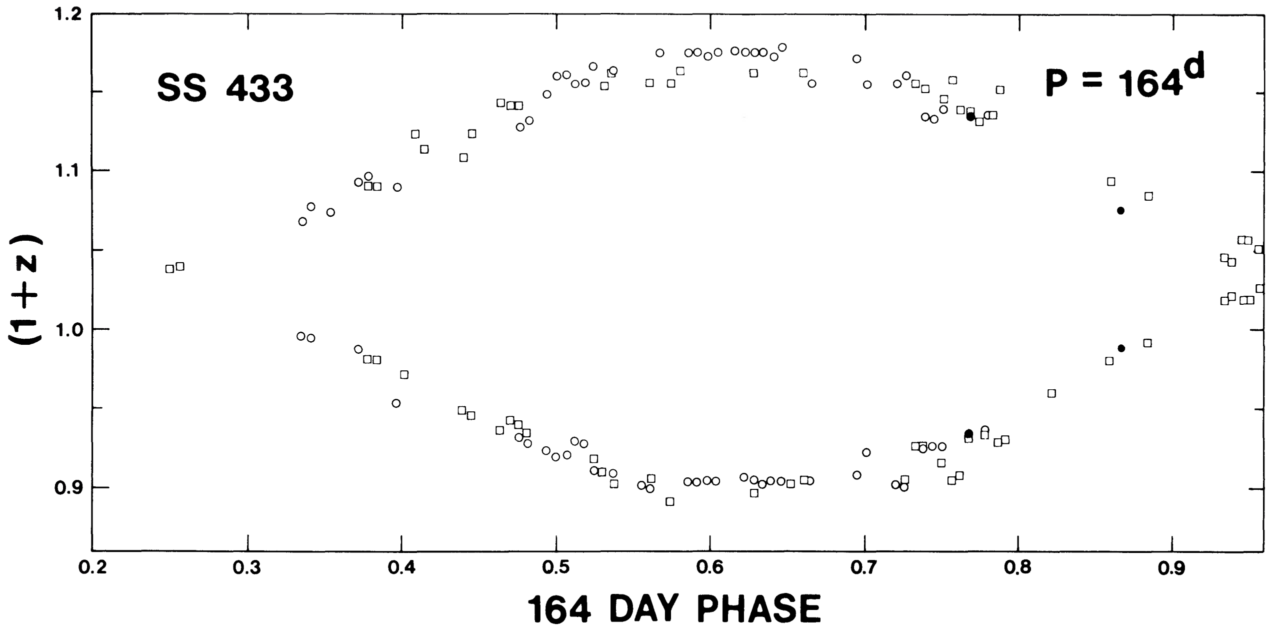

FIG. 3.—SS 433 velocities from Fig. 2, folded with a 164 day period. Different symbols are used to denote data obtained in different cycles of the period, to display the accuracy of superposition of successive cycles. *Filled circles*, 1978 June–July; *open circles*, 1978 September–December; *squares*, 1979 February–June. The phase convention is chosen to parallel (and pun upon) the familiar spectroscopic binary notation: phase zero (approximately JD 2,443,891) occurs when the emission lines cross the γ (Lorentz factor) redshift.

we may consider if the changing velocities are due simply to Keplerian motion. This would indeed be remarkable, as the total system mass implied by the measured period and velocity amplitude is of order $10^9\ M_\odot$. However, the diameter of such an orbit is 2 lt-weeks, and the data of Figure 2 indicate correlated events in the red- and blueshift systems, such as those discussed in § II above, on time scales of 1 day. Thus, barring complex geometry or special initial conditions, causality alone makes the Keplerian interpretation unlikely (see also Abell and Margon 1979; Katz 1979).

Several authors (Milgrom 1979; Fabian and Rees 1979; Katz 1979) have already suggested that two collinear rotating beams may fit our data on SS 433, and a kinematic analysis of our observations (Abell and Margon 1979) verifies this prediction in detail. As a crude explanation of the occasional correlated deviations from the velocity curve, we suggest a temporary change at the central source in the beam velocity (analogous to the mechanism originally suggested by Fabian and Rees [1979] to provide the entire wavelength modulation, now known to be periodic). It has not escaped our attention that two prominent examples of these events, occurring near 1978 December 3 and 1979 May 18 (see Fig. 2), are separated by one 164 day cycle, to within the accuracy of our period determination.

Numerous dynamic and astrophysical problems concerning SS 433 remain to be explained. As the moving-system emission-line widths are small compared with the inferred beam velocity (~5%), the collimation of the beams is apparently excellent. This suggests a possible assessment of the eventual broader significance of this object. Just as radio pulsars observationally demonstrated that conversion of rotational energy into relativistic particles is straightforward, common, and possibly even the norm in compact objects, perhaps SS 433 demonstrates that mass expulsion of near-relativistic material through collimated jets is equally straightforward. If so, the significance to theories of active extragalactic nuclei will be substantial.

We are extremely indebted to a number of colleagues within the University of California system for generously obtaining spectra for us. These observers include Drs. L. H. Aller, E. M. Burbidge, A. Koski, J. Miller, M. Plavec, H. E. Smith, and H. Spinrad. Drs. D. Clark and J. Liebert kindly communicated unpublished observations. Drs. H. Epps and R. K. Ulrich and Mr. B. Wood are largely responsible for the development of the UCLA Reticon system, which was supported in part by a grant from the Research Corporation to H. C. F. Mr. R. Downes and Dr. K. B. Kwitter contributed very substantially to acquisition and reduction of much of the data. For useful theoretical discussions we thank Drs. G. O. Abell, J. I. Katz, J. Roberts, M. Rowan-Robinson, and R. K. Ulrich. This work has been supported by the National Science Foundation, through grants AST 77-27745 and AST 76-21312.

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