THE ASTROPHYSICAL JOURNAL, 230:L41–L45, 1979 May 15

THE BIZARRE SPECTRUM OF SS 433

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Received 1978 December 18; accepted 1979 February 15

ABSTRACT

We report extensive spectrophotometric observations of Stephenson-Sanduleak 433, a peculiar 14th magnitude emission-line object recently identified with a variable nonthermal radio source, and probably also associated with the X-ray source A1909+04. Cassegrain image-tube scanner spectra obtained with the KPNO 4 m and Lick 3 m and 0.6 m reflectors show broad (4000 km s^{-1}), intense Balmer, He I, and He II emission lines which vary dramatically in profile and intensity on a time scale of one day. Coudé scanner data from the Hale 5 m and Mount Wilson 2.5 m telescopes reveal complex, composite Hα profiles. These data also show the interstellar NaD lines to each have equivalent widths of 1.9 ± 0.2 Å, and velocity range remarkably similar to the 21 cm emission profile in this direction, implying a distance for SS 433 in excess of 3.5 kpc. There is no evidence for orbital motion in the emission lines for periods in the range 1–30 days, nor any sign of an underlying stellar absorption spectrum. The most bizarre spectral features, however, are three very strong (equivalent widths 50–150 Å), broad emission features in the green, red, and near-infrared, which change in intensity, profile, and wavelength daily, but apparently aperiodically. These features have been seen to vary in wavelength by up to 600 Å in 30 days. In addition, we present image-tube photography, photoelectric photometry, and proper-motion observations, in an effort to discern the nature of this unusual object. The total proper motion does not exceed $0\overset{''}{.}01$ yr^{-1}; the object is variable by at least 1 mag on a time scale of years.

Subject headings: stars: emission-line — X-rays: binaries — X-rays: sources

I. INTRODUCTION

The 14th magnitude emission-line object Stephenson-Sanduleak 433 (Stephenson and Sanduleak 1977) was first noted on objective prism plates in the mid-1960s, and independently by Krumenaker (1975), where a correct finding chart but erroneous coordinates are given. Although a variable, unresolved radio source in this region was seen by Clark, Green, and Caswell (1975), the association of the radio source with SS 433 was not made until recent independent and essentially contemporaneous observations by several groups (Clark and Murdin 1978, hereafter CM; Feldman *et al.* 1978; Ryle *et al.* 1978; Seaquist, Gregory, and Crane 1978). The first moderate-dispersion spectroscopy of the object has been presented by CM, who also note its positional coincidence with the X-ray source A1909+04 (Seward *et al.* 1976). As these spectra show emission due to He II λ4686 and the C III/N III λλ4640, 4650 blend, a characteristic common to almost all X-ray–star visible counterparts, CM suggest SS 433 as the proper identification of the X-ray source, rather than the supernova remnant W50, located 10′ farther north, as suggested by Seward *et al.* (1976). As stressed by CM, the observed X-ray variability (Seward *et al.* 1976; Marshall *et al.* 1978) also argues for a stellar identification. However, the close proximity to W50, and the unusual radio and optical characteristics of SS 433 have led both CM and Ryle *et al.* (1978) to suggest that the two objects are in fact related, and that SS 433 may represent a new subclass of stellar remnant. In this *Letter* we present a variety of observations of this unusual object, and show that SS 433 exhibits a completely unprecedented level of spectral variability.

II. OBSERVATIONS

We initiated observations of SS 433 on 1978 August 2, and have obtained extensive spectroscopy, together with limited photography and photometry, throughout the remainder of the 1978 observing season. The spectrophotometric observations are too numerous to list or discuss individually here, and so will be summarized as follows. The Robinson-Wampler Image-Tube Scan-

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ner (Robinson and Wampler 1972; Miller, Robinson, and Wampler 1976) was used for Cassegrain spectrophotometry on nine nights at the Lick Observatory 3 m Shane reflector. Wavelengths in the 3800–7300 Å range were covered at various times, generally with 8–10 Å resolution, although constraints of other observing programs dictated the precise wavelengths observed. On several nights observations with 4 Å resolution centered at Hβ were also obtained. An identical scanner on the Lick 0.6 m reflector was used to obtain spectra on 9 additional nights, generally in the 5600–7800 Å range, again with 10 Å resolution. The Intensified Image Dissector Scanner was employed at the Cassegrain focus of the 4 m Mayall reflector of the KPNO on four nights; three nights covered the 4600–5300 Å range with 4 Å resolution, with the remaining night in the 3400–7500 Å band with 10 Å resolution. All of the above data were reduced to absolute fluxes via the observation of one or more spectrophotometric standard stars each night.

Coudé-resolution spectroscopy was obtained on three nights using the Shectman scanner (Shectman and Hiltner 1976) at the Hale 5 m and Mount Wilson 2.5 m reflectors. The Palomar data are centered at Hα and NaD, with 0.6 Å resolution and 300 Å of coverage; the Mount Wilson data are centered at Hα only, with 0.3 Å resolution and 160 Å of coverage. Because of variable light losses at the slit, these scans have not been reduced to absolute fluxes.

In agreement with CM, we find the spectrum to be dominated by intense, variable Balmer and He I emission. Hydrogen lines are visible to at least H8. In addition to the He I λ5876, 6678, 7065 noted by CM, we see also a variety of blue and green He I lines in emission, viz., 4471, 4920, 5016, and 5048. The first three of these lines have very prominent P Cygni profiles on all of the good quality spectra, i.e., a blue-shifted absorption component. These absorptions are in fact the only reliably detected stellar absorption features anywhere in the spectra.

The Balmer and He I emission-line profiles are often more complex than reported by CM. Some of this difference may be due to our higher resolution, but some of the changes are also unquestionably secular as they are easily apparent within subsets of our own data. For example, we have at times seen single-component, broad Hβ and He I λ5876 as in CM. On other occasions, however, a very sharp drop in the flux appears, approximately at the rest wavelength of the emission line, dividing the line in half, with the red side appearing more intense. An example of this phenomenon is shown in Figure 1, where we display the blue-green spectrum of SS 433 on a night where λ5876 is bifurcated. On the following night, a 4 Å resolution spectrum at Hβ, shown in Figure 2, also shows a very prominent bifurcated structure. A 10 Å resolution spectrum in the red on this same night hints at a similar but less deep bifurcation at Hα. Coudé-resolution scans at later times, typified by the result in Figure 2, show a milder asymmetry, perhaps as a result of a superposition of a sharp, intense component at +120 km s^{-1}, on a broad, less intense line centered at the same velocity. All three coudé Hα spectra, obtained on 1978 October 19, 22, and 23, show this same basic structure. The absorption dip at −365 km s^{-1} has the same velocity as the absorption components of the previously mentioned He I P Cygni profiles, to within the accuracy of the respective measurements.

We have searched for radial velocity variations among the narrower H and He lines in our data; He I λ6678 is especially useful for this purpose. On ~20 separate nights spanning ~40 days for which velocities

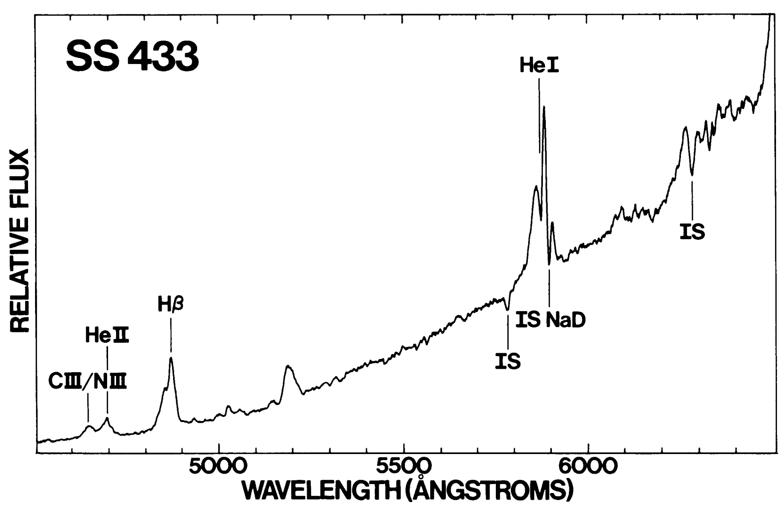

FIG. 1.—The blue/green spectrum of SS 433, obtained on 1978 September 30 at the Lick Observatory 3 m Shane reflector, with 8 Å resolution. The enormous Hα emission line has been truncated for convenience in scaling, and is responsible for the precipitous rise in flux at λ6450. Several interstellar absorption lines and diffuse bands are marked "IS". The complex structure between the interstellar λ6284 band and Hα, discussed in the text, is readily apparent. The unidentified intense emission-line at λ5200 is a typical example of the variable green feature, and He I λ5876 is most probably contaminated by the variable red feature, also discussed in the text. Note the highly reddened continuum slope.

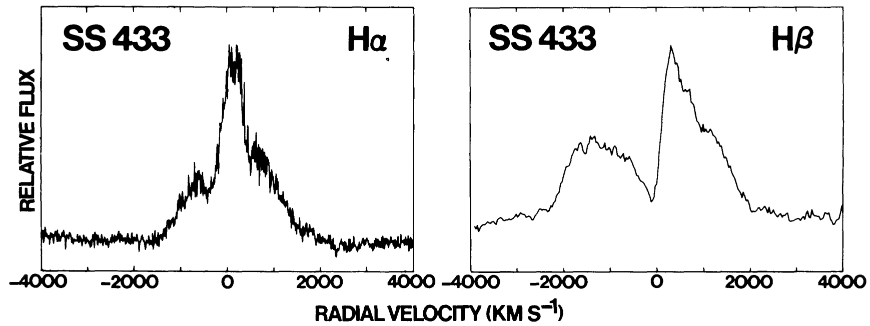

FIG. 2.—High-resolution Balmer-line profiles of SS 433. All wavelengths have been converted for convenience to velocities with respect to the local standard of rest. *Left panel*, the Hα line in SS 433, obtained at the coudé focus of the Hale 5 m reflector with 0.6 Å resolution on 1978 October 19; *right panel*, the SS 433 Hβ profile, obtained with 4 Å resolution at the Lick 3 m Shane reflector on 1978 October 1. Compare this complex structure with the Hβ line of Fig. 1, observed just one day earlier.

can be derived from scanner data, we find no evidence for radial-velocity variability, but to a rather weak upper limit of order ± 100 km s^{-1}. The coudé data place a slightly better limit on the velocity variation of Hα, of ± 50 km s^{-1}. The systemic velocity of SS 433 appears to be modest and positive, although again the width and variability of the features permit only weak limits, $V_0 \lesssim 180$ km s^{-1}.

Virtually all of the emission features undergo changes in equivalent width on a time scale of days. The easiest feature to measure is the enormously strong Hα line, which we have seen change by at least 50% in 1–2 days. For example, on four consecutive nights at the Lick 0.6 m, 1978 October 28–31, we measured Hα equivalent widths of 290, 270, 175, and 180 Å, respectively, with uncertainty $\leq 5\%$.

The higher excitation He II λ4686 and C III/N III λ4650 emission lines reported by CM are generally strong on our spectra (see Fig. 1), although again variable on a time scale of 1 day; on some nights the λ4650 feature is virtually absent. CM also detect an emission line at λ6490 which they suggest may be Fe II. Our spectra in this region are variable and virtually incomprehensible. At times the ~200 Å area between the interstellar/telluric λ6284 absorption band and the blue wing of Hα is filled with a series of irregular emission and/or absorption features, which can change on a time scale of 1 day to one or two broad emission lines, occasionally symmetric or sometimes irregular. The features are entirely absent during some periods; e.g., we have spectra on eight of nine consecutive nights which do not show them. The origin of these features is difficult to explain pending further higher-resolution observations.

Perhaps the strangest of all the unusual spectral features in SS 433 have apparently appeared subsequent to the work of CM. Our spectra, obtained between 1978 September 30 and December 5, show three previously unreported, very strong, broad emission lines in the green, red, and infrared, at unfamiliar wavelengths. Although they vary nightly in intensity, ranging from equivalent widths of a few Å up to 150 Å, they are probably present on every spectrum for which we have suitable wavelength coverage. The green line can be seen in Figure 1, where it appears at λ5190. Examples of the red (~6000 Å) and infrared (~7400 Å) features are given in Figure 3. This latter figure, displaying the spectrum on three nights in a 4 day interval, illustrates that both the profiles and the wavelengths of these features change drastically on very short time scales. In this 4 day period, for example, the infrared line moved to longer wavelengths by 150 Å, which, if interpreted as Doppler motion, corresponds to a change of $+6000$ km s^{-1}. Simultaneously, the red feature moved in the opposite sense toward shorter wavelengths, by 70 Å, corresponding to a velocity change of -3500 km s^{-1}.

We have observed these anomalous emission features to traverse an even larger range of wavelengths. We have spectra spanning eight of nine consecutive nights in the period 1978 October 23–31, for example, where the infrared feature moves almost monotonically from λ7400 to λ7620, while the red feature changes from λ6120 to λ5970, corresponding to $+9000$ km s^{-1} and -7400 km s^{-1}, respectively, if interpreted as Doppler motion. There is evidence for minor but correlated sign reversals in the motions of both lines during this period. If we extrapolate the roughly linear motion of the infrared line back in time across the period 1978 October 8–21, during which we have no data because of the brightness of the moon, we predict wavelengths in the 7000–7200 Å range for the first week of October. We in fact see strong, broad emission lines at λ7040 and λ7165 on spectra obtained on October 3 and 7. These features are now so disparate in wavelength from those discussed above that because we have not tracked them each night we cannot be absolutely certain that they are identical to the λ7400 infrared line. However, the profiles and equivalent widths are similar, and they are an excellent match to the extrapolated wavelengths. If this is the same line, it has moved to the red, in a roughly linear fashion, by 600 Å in 28 days, corresponding to a velocity change of 25,000 km s^{-1}.

Similarly, we have strong evidence that the red feature can appear at wavelengths as short as λ5850, blending with the already strong He I λ5876 emission. On spectra obtained both 3 weeks before and after the eight-night sequence described above, the emission at λ5876 is far stronger and broader than the other He I lines, suggesting that it is contaminated by the moving red emission feature. Most significantly, on November 29 the emission line is seen to move back toward the red, appearing at λ6060 and clearly split from He I λ5876. Thus if all of these observations are of the same red line, as seems likely, it has changed in velocity by at least 12,000 km s^{-1} in 30 days, and in roughly 60 days has made a complete traverse from λ5850 to λ6120 and return, with evidence of a new cycle to the red beginning immediately thereafter. Our data on the green line are more fragmentary, but we have observed it to appear over the range λλ5020–5340 in a 30 day period. We consider possible explanations of these strange features in a subsequent paper.

III. REDDENING AND DISTANCE

In agreement with CM, we find SS 433 to show signs of substantial interstellar reddening. There are strong interstellar λ4430, λ5778/80, and λ6284 bands on all of our spectra, as well as prominent NaD lines, which are unresolved in our scanner data. A Hale 5 m coudé spectrum of 1978 October 18 resolves the Na doublet into two broad components, each of equivalent width 1.9 ± 0.2 Å. The lines have essentially square profiles with residual relative intensity 0.05 ± 0.07. This minimum extends from velocity $v = v_{\rm LSR}$ to $v = v_{\rm LSR} + 85$ km s^{-1} for D_1, and from $v = v_{\rm LSR}$ to $v = v_{\rm LSR} + 65$ km s^{-1} for D_2. The circumstellar NaD lines observed by Ulrich and Knapp (1979) in T Tauri stars do not have this distinctive square profile, and their absorptions at velocities other than $v_{\rm LSR}$ are not uniformly saturated. We conclude that these features in SS 433 are interstellar. The survey by Hobbs (1969) of interstellar D-line profiles with high spectral resolution shows that individual clouds contribute features of width 2–5 km s^{-1}. Broad absorptions with uniformly low residual intensity occur for stars at distances at or beyond 1 kpc. Such features are less than 20 km s^{-1} wide in all cases. Thus we attribute the additional breadth of NaD absorption in SS 433 to galactic rotation. We take 50 km s^{-1} as a conservative estimate of the galaxy-induced velocity dispersion. Using rotation parameters given by Gunn, Knapp, and Tremaine (1979), the distance implied for SS 433 is approximately 3.5 kpc. The Weaver and Williams (1973) H I survey shows that the bulk of neutral hydrogen in this direction lies between velocity limits remarkably similar to those we find for NaD absorption. Thus SS 433 may lie entirely beyond the gas layer, at a distance substantially greater than 3.5 kpc.

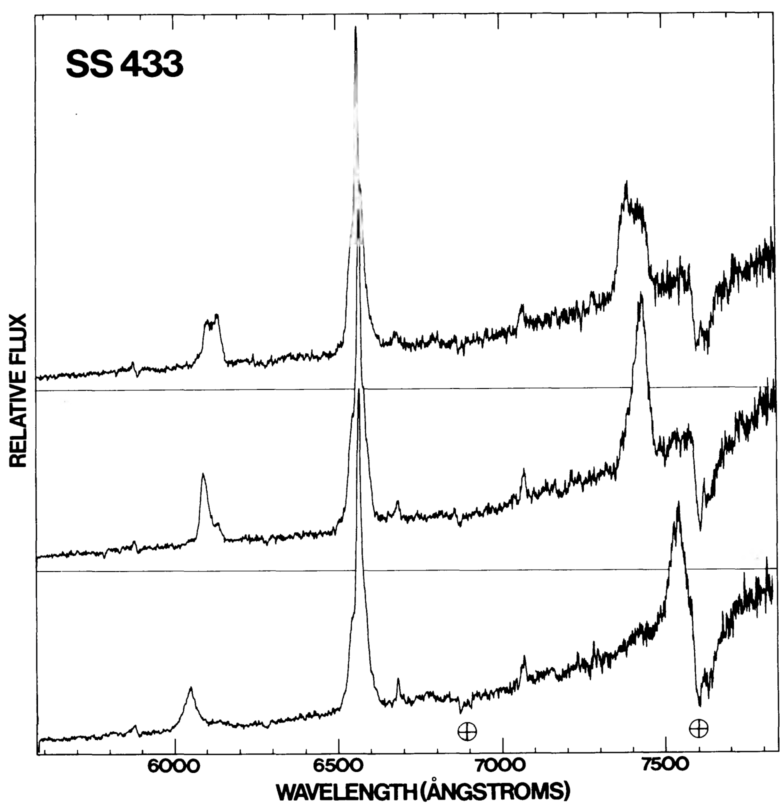

FIG. 3.—The red/infrared spectrum of SS 433 on three of four consecutive nights, obtained with 10 Å resolution on the Lick 0.6 m reflector. The dramatic changes in both wavelength and profile of the two unidentified emission features flanking Hα are well-illustrated in this example. He I λ5876, 6678, 7065 emission is visible, as are the unresolved interstellar NaD lines and λ6284 band. The emission bands in the λλ6300–6400 range (cf. Fig. 1) are absent on these particular nights. The telluric A and B bands have been indicated. The upper, center, and lower panels were observed on 1978 October 23, 24, and 26, respectively.

We may use the observed equivalent widths of the diffuse interstellar bands to estimate the color excess of SS 433, thus avoiding the generally poor correlation of NaD equivalent width with color excess (Bromage and Nandy 1973). We find a λ4430 equivalent width of 1.7 Å, implying $E(B-V) = 0.75$ (Herbig 1975), and a λ5778/80 width of 1.0 Å (averaged from three spectra), yielding $E(B-V) = 0.70$ (Herbig 1975). We have not measured the λ6284 band, as at scanner resolution it is normally severely contaminated by telluric components. Our values for the color excess are substantially less than those inferred by CM, using a similar procedure.

As we have good evidence that SS 433 lies beyond most or all of the galactic H I layer, the measured 21 cm column density will also be a reasonable reddening estimator. The Weaver and Williams (1973) data have kindly been velocity-integrated for us by Dr. H. Weaver, who finds at the location of SS 433 the value $N(\text{H I}) = 8 \times 10^{21}$ atoms cm^{-2}. Using the correlation of Bohlin, Savage, and Drake (1978), we find $E(B-V) \geq 1.4$, where the inequality is due to the unknown column density of molecular hydrogen. That this value exceeds that inferred from the diffuse bands is not unusual in regions of high reddening, where the widths of these bands are often found to be deficient with respect to color excess (Snow and Cohen 1974).

We have measured photoelectric magnitudes and colors for SS 433 on 1978 October 6 using the Lick 0.9 m Crossley reflector, and find $V = 14.22 \pm 0.04$, $(B-V) = 2.06 \pm 0.10$, $(U-B) = 0.61 \pm 0.10$. These colors are in reasonable agreement with the (less precise) values implied by our spectrophotometric observations, and those of CM. Adopting $R = A_v/E(B-V) = 3.3$, we thus infer that SS 433 is a luminous object, with $M_V \leq -3.1$.

The proper motion of SS 433 was measured using blue plates taken with the Lick Observatory 51 cm astrograph at epochs 1947, 1949, 1973, and 1977. The relative proper motions, measured with respect to anonymous reference stars of estimated mean blue magnitude 15, were corrected for solar and galactic motion to yield the following equatorial components of absolute proper motion: $\mu_\alpha = +0''.003$ yr^{-1}, $\mu_\delta = -0''.012$ yr^{-1}. The estimated uncertainty of these motions is of the order $\pm 0''.005$ yr^{-1}. The plate material was also examined for possible variability of the light from SS 433. On the basis of uncalibrated iris photometer readings, it was found that at epoch 1949 the object was brighter by 1.0 ± 0.2 mag than at the other three epochs, at which times it appeared to be constant to within 0.2 mag.

The strong emission-line spectrum of SS 433, plus its proximity to the supernova remnant W50, suggest that a search for surrounding nebulosity might be profitable. To this end, four deep plates of the field were obtained, two each in bandpasses of 5500–5900 Å and 6510–6610 Å, using a Varo image-tube camera at the Lick 36 inch (0.9 m) refractor. These plates go as deep as the *Sky Survey* plates of the region, but at a far superior angular scale, 11″ mm^{-1}. SS 433 is stellar on all of these plates, and there is no evidence of surrounding nebulosity.

Clark and Murdin (1978) have suggested a strong spectral resemblance of SS 433 to Circinus X-1 (Whelan *et al.* 1977). Although both objects are heavily reddened and show strong Balmer and He I emission, our spectral data indicate that SS 433 is different and probably the considerably more exotic of the two objects.

We are indebted to Dr. D. Clark for stimulating our interest in SS 433 prior to publication of his data, to Drs. G. R. Knapp, S. A. Lamb, H. Spinrad, and P. Szkody for several observations, to Dr. D. Jenner and Messrs. R. Downes, E. A. Harlan, and L. Webster for aid in obtaining and reducing data, and to Drs. R. Angel, M. Jura, J. Liebert, and H. Weaver for useful discussions. We gratefully acknowledge the financial support of the National Science Foundation, through grants AST 77-27745 (B. M.), AST 76-21312 (H. C. F.), AST 76-20260 (R. K. U.), and AST 76-81342 (A. K.), and of NASA through grant NSG 7341 (J. I. K.).

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Note added in proof.—Further analysis has provided conclusive evidence that the unidentified emission features are Doppler shifted Balmer lines at a displacement which has varied from 20,000 to 50,000 km s^{-1}. A complete discussion is in preparation.