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THE EXTRAORDINARY COMPOSITION OF U AQUARII[1]

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ABSTRACT

U Aquarii is a cool, faint R CrB type variable star. Its spectrum has been found to show the following remarkable features: no trace of hydrogen absorption lines or CH bands, strong bands of $^{12}C_2$ and CN, and extraordinarily strong lines of Sr II and Y II. U Aquarii is the first hydrogen-deficient carbon star known to show enhanced abundances of *s*-process elements; but the *s*-processing was unusual in that it produced Sr and Y abundances of about 100 times normal, but little or no Ba. It is suggested that U Aqr is the helium-carbon core of an evolved star of about 1 $M_\odot$ that ejected most of its hydrogen-rich envelope at the helium core flash. The *s*-process abundances can most easily be understood in terms of a single neutron exposure that occurred at the core flash, characterized by neutron exposure $\tau \approx 0.6$ mb^{-1}.

Subject headings: nucleosynthesis — Stars: abundances — stars: hydrogen-deficient — stars: individual — stars: R Coronae Borealis

I. INTRODUCTION AND OBSERVATIONAL DATA

While carrying out an objective-prism survey in regions at high galactic latitudes, one of us (H. E. B.) noticed the unusual spectrum of a fairly cool carbon star that proved to be the variable U Aquarii (1900 position: $21^h57^m.9$, $-17°06'.6$; galactic coordinates $l = 39°$, $b = -50°$). The objective-prism plate was obtained with the Michigan Curtis Schmidt telescope at Cerro Tololo Inter-American Observatory (CTIO); subsequently, slit spectrograms were obtained with the CTIO 4 m reflector.

The extraordinary feature noted in the spectrum of U Aqr was the unprecedented strength of its Sr II absorption lines. In fact, U Aqr is the star with the strongest known strontium lines, Sr II 4077 and 4215 being comparable in strength to the Ca II H and K lines! In this paper we will discuss this strontium enhancement in terms of an unusual *s*-processing event.

U Aquarii is listed in the variable-star literature as an R CrB type variable that ranges from 10.5 to fainter than 14.4 photographic magnitude. R Coronae Borealis variables are known to be hydrogen-deficient, carbon-rich stars (Bidelman 1953, 1956; Warner 1967; Feast 1975), and it is clear that U Aqr shows these composition anomalies. Figure 1 (Plate 4) shows a 47 Å mm^{-1} image-tube slit spectrogram of U Aqr, obtained with the CTIO 4 m telescope on 1976 June 6, when the variable was near maximum light. For comparison, a spectrogram of HD 182040, a well-known, nonvariable hydrogen-deficient carbon star (Bidelman 1953), is also shown. Neither star's spectrum shows Balmer absorption lines or CH bands. The atomic spectra appear roughly comparable (aside from the obvious differences in the *s*-process elements). The bands of CN with heads at 3883 and 4215 Å, and $^{12}C_2$ at 4737 Å, are strong in both stars, but there is no trace of the $^{12}C^{13}C$ or $^{13}C_2$ band heads at 4744 Å and 4751 Å that are often seen in normal carbon stars (cf. McKellar 1960, Plate I). The very striking enhancement of Sr II in the spectrum of U Aqr is easily seen in Figure 1.

Although spectroscopically less prominent, lines of Y II are also considerably strengthened in U Aqr. However, there is no significant enhancement of Ba II.

The peculiarities of hydrogen-deficient stars are usually attributed to loss of a hydrogen-rich envelope, exposing a helium-rich stellar core. Helium burning to ^{12}C has taken place in this core, as shown by the strong $^{12}C_2$ molecular bands.

A characteristic of several R CrB variables at minimum light is the presence of strong He I 3889 chromospheric emission (Herbig 1949; Payne-Gaposchkin 1963; Alexander *et al.* 1972). U Aquarii shares this characteristic, as can be seen in Fig. 2, which shows a low-resolution scan taken by H. E. B. with the image-dissector scanner on the Kitt Peak 2.1 m reflector on 1977 September 7. U Aquarii was very faint at that time, and showed very strong He I emission. A satisfactory explanation for the presence of this single He I emission line is not to our knowledge available.

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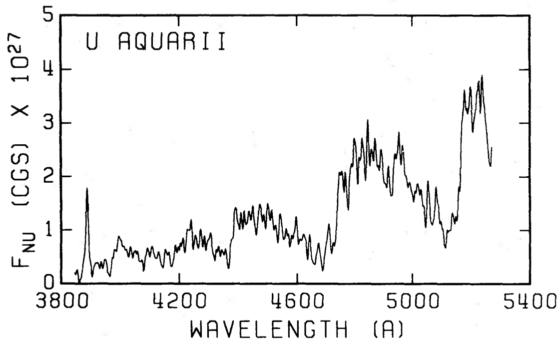

FIG. 2.—Kitt Peak scan of U Aqr at minimum light. Note strong He I 3889 emission. The strong molecular absorption bands are due to $^{12}C_2$.

Dr. M. W. Feast has informed us that U Aqr shows an infrared (3.5 μm) excess, which is also typical of R CrB variables.

It thus appears that, aside from the very large strengths of Sr II and Y II, U Aqr is a fairly typical R CrB type variable.

Intensity tracings of the spectrograms of U Aqr and HD 182040 were prepared with the aid of the PDS microdensitometer at KPNO and computer reduction programs written by R. E. L. These tracings show $^{12}C_2$ to have comparable strengths in both U Aqr and HD 182040, while CN is somewhat stronger in HD 182040. It is difficult to determine equivalent widths of spectral lines from these tracings, due to uncertainties in continuum placement and strong blending of spectral features at the resolution of our material. We list in Table 1 the equivalent widths of a few strong lines that we consider to be least affected by these problems. The 4215 Å line of Sr II was not measured because, although it is very strong in U Aqr and could be measured, it is inextricably blended with the nearby strong CN band head in HD 182040, and hence the line is unusable in a differential analysis. We believe that our equivalent widths are accurate to approximately $\pm 25\%$. Fortunately, we will need to use these equivalent widths only differentially between the two stars.

II. CHEMICAL ABUNDANCES

From the present material, it is apparent that only a very crude abundance analysis is warranted.

TABLE 1

EQUIVALENT WIDTHS

Line	W (U Aqr) (Å)	W (HD 182040) (Å)
Ca I 4226	0.8:	2.0
Ca II 3933	13.2	20.0
3968	9.8	16.1
Fe I 4045	1.4	1.6
4063	0.7	1.2
Sr II 4077	11.4	2.4
Y II 3950	1.6	< 0.15
Ba II 4554	1.4	1.7

Obviously, spectrograms of much higher resolution would be desirable;[4] however, we note that Deutsch (1966) has shown that even data of modest quality can yield surprisingly reliable abundance determinations.

We will attempt to obtain abundances in U Aqr differentially with respect to HD 182040. First, we give *UBV* photometry for the two stars in Table 2; two observations were made of U Aqr, one near maximum light (the relevant observation for comparison with the nonvariable HD 182040), and the other during its 1976 autumn minimum.

Allowing for the fact that HD 182040 lies at a moderately low galactic latitude (−13°) and may be somewhat reddened, we conclude from the photometry that the two stars have roughly the same temperatures.

We will also assume that the two stars have the same surface gravities. Support for this assumption comes from the evidence that hydrogen-deficient carbon stars have a fairly small range of absolute magnitudes, averaging near $M_v = -4$ (Warner 1967; Feast 1975).

The justification for the differential analysis can also be based on the spectroscopic comparability of U Aqr and HD 182040. The rough equality of the ratio Ca II/Ca I in the two stars implies that both objects have similar levels of ionization, and hence comparable effective temperatures and gravities. The comparability of the effective temperatures is, as previously stated, also deducible from broad-band colors. Given that the atmospheric parameters of the two objects are roughly equal, one can then use the excitation temperature and electron pressure of HD 182040 as given by Warner (1967) to establish that the singly ionized state is the predominant ionization stage of most species in both stars, and hence proceed to the differential analysis on this basis.

Under these assumptions, and for lines on the square-root portion of the curve of growth (as are all lines in Table 1), the ratio of equivalent widths of the same spectral line of an element in the two stars is

$$\frac{W_{\rm el}(\rm U\ Aqr)}{W_{\rm el}(182040)} = \{(N_{\rm el}/N_{\rm op})_{\rm U\ Aqr}/(N_{\rm el}/N_{\rm op})_{182040}\}^{1/2}$$

$$= \left\{\frac{(N_{\rm el}/N_{\rm Fe})_{\rm U\ Aqr}}{(N_{\rm el}/N_{\rm Fe})_{182040}}\frac{(N_{\rm Fe}/N_{\rm op})_{\rm U\ Aqr}}{(N_{\rm Fe}/N_{\rm op})_{182040}}\right\}^{1/2},$$

where $N_{\rm op}$ is the number density of the species responsible for the continuous opacity. According to Warner's (1967) discussion of HD 182040, this species is carbon, with a smaller contribution from helium.

In the usual logarithmic bracket notation, we have, for U Aqr relative to HD 182040,

$$[N_{\rm el}/N_{\rm Fe}] = 2[W] - [N_{\rm Fe}/N_{\rm op}] .$$

We note that such element-to-iron abundance ratios

[4] An attempt by H. E. B. to obtain a 5 Å mm^{-1} echellogram of U Aqr with the KPNO 4 m telescope in 1976 October was thwarted when the variable was found to have dropped to minimum light!

TABLE 2

UBV PHOTOMETRY

Star	V	$B-V$	$U-B$	Source
U Aqr..............	11.25	0.99	0.38	CTIO 0.9 m, 1975 Nov 14
U Aqr..............	13.94	1.30	0.63	KPNO 0.9 m, 1976 Sept. 30
HD 182040...........	7.01	1.09	0.63	Mendoza and Johnson 1965

will be very close to being relative to the solar values, since Warner (1967) found essentially solar abundance ratios among all elements heavier than carbon measured in HD 182040.

From the equivalent widths of the two Fe I lines given in Table 1, we find $[N_{Fe}/N_{op}] = -0.3 \pm 0.2$. For other elements relative to iron, the abundances are given in Table 3. It is difficult to state what errors should be associated with the entries in Table 3, but the internal agreement of the two iron lines mentioned above, as well as the similar internal agreement among the three calcium lines, gives us some confidence that our true errors may be smaller than about ± 0.5 dex.

We conclude that, within the errors, the calcium abundance is solar. Strontium and yttrium are enhanced by factors near 100 (this is a lower limit in the case of Y, which is not detectable in HD 182040); but barium is *not* significantly enhanced.

III. *s*-PROCESSING IN U AQUARII

U Aquarii is the only star known to combine the following abundance peculiarities: (1) an extreme hydrogen deficiency, as shown by the absence of CH bands and Balmer lines, which may be due to hydrogen burning or loss of a hydrogen-rich envelope; (2) strong $^{12}C_2$ and CN bands, indicative of helium burning; and (3) strong lines of certain elements with isotopes whose synthesis is usually attributed to the *s*-process of neutron-capture reactions. As the abundances listed in Table 3 show, the *s*-processing in U Aqr was of a type that has not previously been encountered: Sr and Y were produced in copious quantities, but Ba apparently not at all.

The σN_s curves of most *s*-process–enhanced stars show the familiar ledge-precipice structure that is also characteristic of solar-system material. This can easily be understood as the consequence of a distribution of neutron exposures, with a weighting function that has usually been taken to be an exponential or power law (Clayton *et al.* 1961; Clayton 1968; Ward and Newman 1978). We therefore consider first whether such an exposure history can explain the *s*-process abundances in U Aqr.

In Figures 3 and 4, we have used an exposure distribution with weighting function $C \exp(-\tau/\tau_0)$ and the exact solution of Ulrich (1973) and Clayton and Ward (1974). These calculations show that it is indeed possible to produce large overabundances of Sr and Y relative to Ba, if the value of τ_0 is sufficiently small. But unfortunately, as shown in Figure 3, the abundance of the Sr-Y group in this case would be expected to be very small relative to that of the iron peak, in contrast to the situation in U Aqr. Figure 4 shows clearly that it is possible to obtain large Sr/Ba and Y/Ba enhancement factors with $\tau_0 \lesssim 0.05$ mb^{-1}, but the difficulty with the Sr/Fe and Y/Fe ratios

TABLE 3

LOGARITHMIC ABUNDANCES IN U AQUARII RELATIVE TO IRON

Species	$[N_{el}/N_{Fe}]$[a]
Ca I........................	−0.5:
Ca II 3933..................	−0.1
Ca II 3968..................	−0.1
Sr II.......................	+1.7
Y II........................	>2.4
Ba II.......................	+0.1

[a] $[N_{el}/N_{Fe}] = \log(N_{el}/N_{Fe})_{U\,Aqr} - \log(N_{el}/N_{Fe})_{HD\,182040}$.

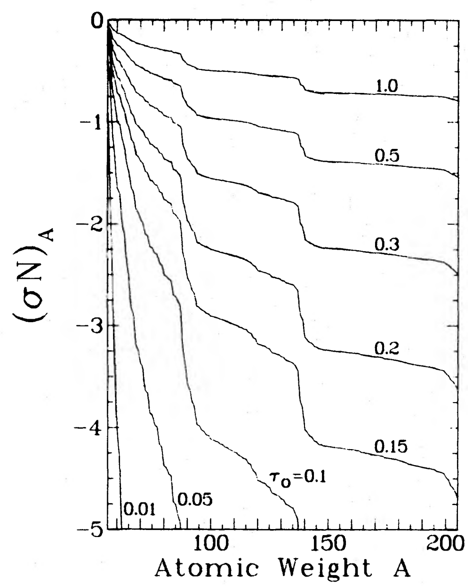

FIG. 3.—Plot of log (σN_s) versus A for an exponential exposure distribution. The neutron-capture cross section σ (mb) times the *s*-process contribution N_s to the abundance by number (normalized to $\sigma N_s = 1$ for the ^{56}Fe seed nuclei at neutron exposure $\tau = 0$) is displayed as a function of atomic weight A for various values of the parameter τ_0 (mb^{-1}) of the exponential exposure distribution. For large values of τ_0 the distribution shows the ledge-precipice structure characteristic of the solar-system abundances (for which the best fit is obtained for $\tau_0 \approx 0.25$ mb^{-1}; see Ward and Newman 1978). For very weak exponential distributions ($\tau_0 \lesssim 0.05$), large abundances of Sr and Y ($A \approx 90$) relative to Ba ($A \approx 140$) can be achieved. The vertical axis should be labeled log (σN_s).

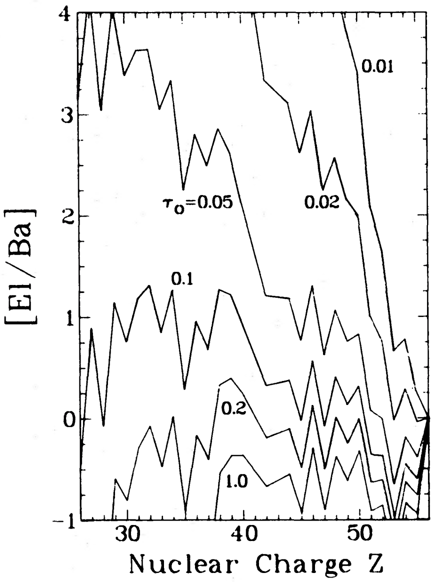

FIG. 4.—Elemental overabundance factors/Ba overabundance factor versus nuclear charge Z for an exponential exposure distribution. The ratio of the s-process yield for each element (El) summed over isotopes and normalized by the solar-system abundance to the same quantity for Ba is displayed in the usual logarithmic bracket notation. Overabundance factors relative to Ba ($Z = 56$) for Sr ($Z = 38$) and Y ($Z = 39$) exceeding those observed in U Aqr can only be obtained for $\tau_0 \lesssim 0.05$, but in that case excessively large Fe/Sr and Fe/Y ratios would also be expected (see Fig. 3).

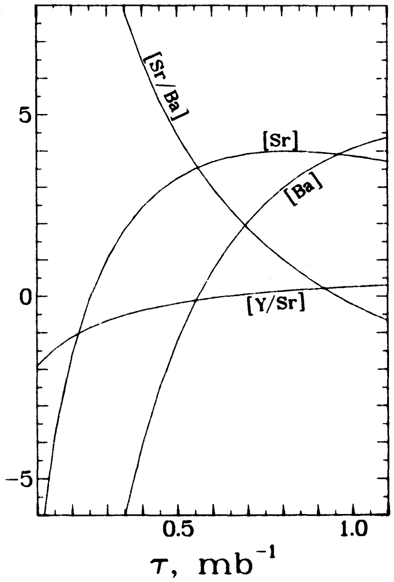

FIG. 5.—Sr, Y, and Ba overabundance factors versus neutron exposure τ for a single-exposure event. The overabundance factors are relative to solar abundances, and are given in the standard logarithmic bracket notation for [Sr], [Ba], [Sr/Ba], and [Y/Sr] as a function of the integrated neutron exposure τ (mb^{-1} = 10^{27} cm^{-2}). The peak of the abundance distribution moves out in atomic weight as τ increases, so that Sr and Y are synthesized in large amounts for moderate values of τ, and Ba for larger values. [Sr/Ba] $\approx$ 2, as observed in U Aqr, would require $\tau \approx 0.7$ mb^{-1}, but somewhat lower values of τ are possible if the processed material has been diluted with unprocessed material.

remains. A discussion of weak s-process irradiations has been given by Peters, Fowler, and Clayton (1972).

The abundances in U Aqr can more easily be explained as the result of a single-exposure event, as illustrated by Clayton (1968, Fig. 7-22) or Newman (1978, Fig. 1). As the strength of the neutron exposure increases, the peak of the abundance distribution shifts from Fe toward the Sr-Y region, and later toward Ba, with the results shown in Figure 5. (Here the single-exposure calculations were made with the exact solution of the unbranched s-process starting from ^{56}Fe seeds, as discussed by Newman 1978.) The Sr/Ba and Y/Ba ratios can be many orders of magnitude larger than solar for weak irradiations, but decrease rapidly as the flow proceeds to larger atomic weights and significant amounts of Ba are synthesized. Also shown in Figure 5 is [Y/Sr], which is near zero except at very weak exposures; but with the present observational material a meaningful value for this ratio in U Aqr cannot be determined.

In reaching the surface of the star, the synthesized material is undoubtedly diluted by mixing with material without s-process enhancements. (Such material could be core material that was not neutron-irradiated. It cannot have been envelope material in the case of U Aqr, unless hydrogen was destroyed throughout the envelope before the mixing.) If an irradiated region of mass M_1 where species i has mass fraction $X_1{}^i$ has mixed with an unprocessed region of mass M_2 where it has mass fraction $X_2{}^i$, then the observed average composition will be

$$\bar{X}^i = (1/f)X_1{}^i + (1 - 1/f)X_2{}^i ,$$

where $f = (M_1 + M_2)/M_1$ is the dilution factor. With no dilution ($f = 1$), Figure 5 indicates that the observed Sr/Ba ratio in U Aqr requires $\tau \approx 0.7$ mb^{-1}. A smaller exposure, $\tau \approx 0.5$ mb^{-1}, would require a dilution factor $f \approx 300$ to give [Sr/Ba] $\approx$ 2. Dilution with un-s-processed core material seems likely to have occurred in U Aqr, since there is little Fe depletion and a high ^{12}C abundance.

For the large overabundances which seem to characterize the s-process isotopes near the Sr-Y peak in U Aqr, $X_2{}^i$ can be neglected in the above expression, which then reduces to $\bar{X}^i = X_1{}^i/f$, so that all the important abundances will scale by approximately the same factor of $1/f$. In Figure 6 we have normalized to the Ba abundance at $\tau = 0.6$ mb^{-1}, which allows [Sr/Ba] $\approx$ 2 with a dilution factor $f \approx 10$, and the resulting distribution that is shown should be representative of the elemental abundance distribution in U Aqr. Zirconium does not have a few strong lines as do Sr, Y, and Ba, so it could not be measured on our spectrograms; however, higher-dispersion spectrograms would be expected to show large Zr overabundances. A search for Tc ($Z = 43$) would also be of interest; its enhancement factor is not shown in

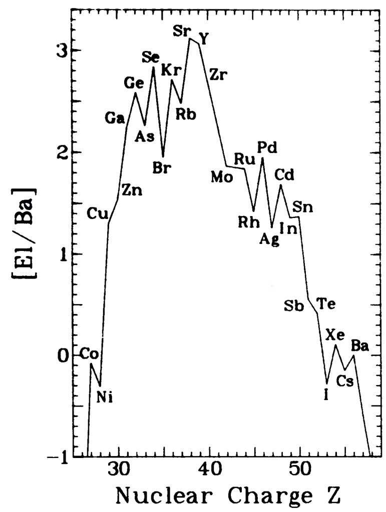

FIG. 6.—Elemental overabundance factors/Ba overabundance factor versus nuclear charge Z for a single-exposure event characterized by $\tau = 0.6\ \mathrm{mb}^{-1}$; the same plot as Fig. 4, but for a single-exposure irradiation. It is seen to be possible to achieve large overabundances of Sr and Y with little synthesis of Ba or other elements away from the Sr-Y region. Ge, Se, Kr, Zr, and other species that should be present in relatively large amounts in U Aqr are not detectable with the present observational material. Observations of U Aqr at higher spectral resolution would be very useful for distinguishing between the abundance pattern shown here and that of Fig. 4.

Figure 6, since its zero solar-system abundance makes the normalization awkward, but it is expected to be synthesized in amounts comparable to neighboring Mo and Ru. Whether any Tc remains on the surface of U Aqr depends on the time elapsed since the *s*-process event. Unfortunately, many of the other elements predicted to have high abundances in U Aqr do not have strong lines in the observable spectral regions, so it will be difficult to confirm other details of Figure 6.

IV. DISCUSSION

Some stellar-population information is available for U Aqr. If it has a typical absolute magnitude of about $M_v = -4$ (at maximum light), its faint apparent magnitude requires it to lie several kiloparsecs below the galactic plane. Its radial velocity, measured on the 4 m spectrograms, has the high value $+103 \pm 20\ \mathrm{km\ s^{-1}}$. It seems clear, then, that U Aqr belongs to an old stellar population, and that its main-sequence progenitor must have had a mass near $1\ M_\odot$. Therefore, it does not seem likely that the *s*-process event whose products are observed on its surface occurred in the helium-shell flashes of an intermediate-mass star, which have gained favor in recent years as the site of the solar-system *s*-processing (Iben 1975; Ward, Newman, and Clayton 1976; Ward and Newman 1978). In fact, as Ulrich (1973) has pointed out, the intermediate-mass-star environment naturally gives rise to an exponential exposure distribution, which, as we have seen, does not well characterize the *s*-process event in U Aqr.

It seems more likely that the *s*-processing in U Aqr was the result of a single helium core flash that occurred shortly after the end of main-sequence hydrogen burning. In this particular case, the core flash succeeded in inducing mixing of envelope material into the He-burning region, as suggested by Cameron and Fowler (1971), and resulted in a brief neutron irradiation ($\tau = 0.6\ \mathrm{mb}^{-1}$ corresponds only to about 30 neutrons captured per ^{56}Fe seed), as well as ejection of the hydrogen envelope. Support for this scenario comes from the work of Despain (1976, 1977), who found strong neutron sources and sufficient energy release to disrupt the envelope when mixing at the helium core flash was investigated in evolved giants of somewhat larger mass (see also Sackmann, Smith, and Despain 1974).

Although we favor the above hypothesis, it may be possible that some or all of the envelope loss was unrelated to the internal mixing and nucleosynthesis, but occurred later, either via relatively slow mass loss, or in response to helium shell flashes (Schönberner 1975, 1977; Renzini 1978). It has even been suggested that hydrogen-deficient stars can dispose of their hydrogen by burning it rather than ejecting it, as a consequence of complete mixing of the star (Paczyński 1971; see also Wheeler 1978). A plausible suggestion might be that U Aqr was the consequence of core-helium-flash mixing and envelope ejection, while the "normal" hydrogen-deficient carbon stars originate in one of the other fashions mentioned in this paragraph.

In summary, U Aqr is a hydrogen-deficient carbon star in which it appears that a single-exposure *s*-processing event has occurred. We suggest an interpretation in which U Aqr is the helium-carbon core of a low-mass star that ejected most or all of its hydrogen-rich envelope during mixing induced by the helium core flash. Further observations at higher spectral resolution would be of great interest, and could test the validity of our interpretation.

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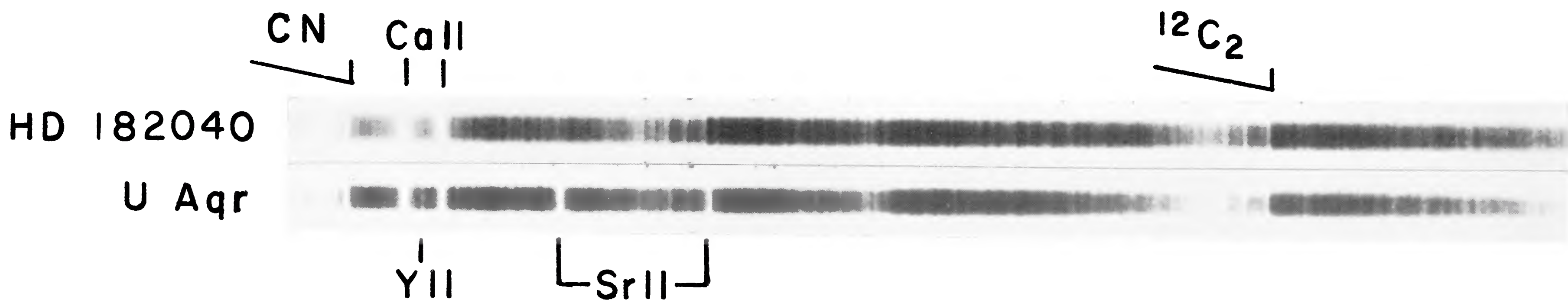

FIG. 1.—Reproductions of 47 Å mm^{-1} image-tube spectrograms of HD 182040 and U Aqr near maximum light. Note strong CN and $^{12}C_2$ bands in both hydrogen-deficient carbon stars, and strong enhancement of Sr II and Y II in U Aqr. The spectrograms cover the range 3800–5000 Å.

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