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RECENT WORK ON RV TAURI STARS

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Abstract

The RV Tauri stars are pulsating variables of high luminosity whose periods are intermediate to those of the Cepheid variables and Mira variables. Since their photometric behavior tends to be rather irregular, they require continual monitoring. A list of the 25 brightest RV Tauri stars is given. A recent spectroscopic study by Wahlgren has indicated that all RV Tauri stars are metal-deficient, but by varying amounts; most appear to belong to the Old Disk population. The TiO band strength in R Scuti has been monitored by narrow-band photometry from the time of a deep minimum until the subsequent maximum; the anomalous strength of these temperature-sensitive bands indicates that the atmosphere is greatly extended.

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1. Introduction

The stars of the RV Tauri class are yellow supergiant variables bridging the gap between the better-known Cepheids and Mira variables. Because they are few in number and of uncertain evolutionary status, they are often completely omitted from discussions of variable stars. They do, however, possess a number of properties that can be fascinating to the observer, and enough progress has been made in recent spectroscopic studies to encourage us to think we are not far from understanding how they fit into the general scheme of stellar evolution.

This paper will serve both to review the basic properties of RV Tauri stars and to discuss some work on them done recently at the Ohio State University. I will also take this opportunity to emphasize that the light curves provided by visual observers continue to play an indispensable role in their study, and that observers with photoelectric photometers can contribute important additional information by measuring narrow-band indices as well as magnitudes.

2. Properties of RV Tauri Stars

The periods of RV Tauri stars range from about 30 to 150 days — extending, that is, from the long-period Cepheids to the short-period Miras. Variables with periods in this range tend to be rather irregular and to display alternating deep and shallow minima. In fact, such an alternation is often taken to be part of the definition of an RV Tauri variable, and the quoted period is then the time between successive deep minima.

Sometimes the alternation of deep and shallow minima is clearly defined, as in the case of the observations of AC Herculis shown in Figure 1. But other stars — or the same star at other times — may show seemingly random variations. As an example of the latter behavior, the visual and photographic light curves of R Scuti, as determined at Harvard for the years 1927-1932 (Payne-Gaposchkin, Brenton, and Gaposchkin 1943), are shown in Figure 2. Strikingly deep minima occur from time to time but not with any apparent regularity. Certainly it would be misleading to imply that every second minimum of R Sct is a deep one. Yet the average cycle length of 140.2 days has persisted for at least several decades.

When a star shows successive minima of nearly the same depth (apart from random fluctuations), it is not always clear whether the period published for it is the time between successive minima or between alternate minima. The convention normally followed is that if a star is called an RV Tauri variable, then the cycle length embraces two minima, whereas Cepheids show only one minimum per cycle. There may be stars catalogued as 50-day RV Tauri variables which could equally well be called 25-day Cepheids, and vice versa. A choice can usually be made on the basis of the shape of the light curve and the degree of regularity, but some variables cannot be properly classified without a careful examination of the spectrum.

It is clear that RV Tauri variables, like Miras, need to be monitored continually. Extensive light curves not only define the behavior pattern of each star but also enable astronomers to look back to see what a star was doing at the time some spectroscopic or photometric observation was made. Visual observers can also perform a valuable service by alerting observatories whenever one of these stars plunges into a deep minimum.

Although the light variation of an RV Tauri star may reach 3^m or more between extremes, the variation in a given cycle is typically only 1^m or less. Consequently, visual estimates of high accuracy are needed to define the star's behavior. It is probably not very useful for hundreds of observers, with their differing personal systematic errors, to send a few observations each to AAVSO Headquarters. It would be more useful if interested observers would "adopt" a few RV Tauri stars, observe them at frequent intervals, and aim for the highest possible consistency. This is the approach taken by Daniel Horowitz, and his paper on CT Orionis at this symposium (Horowitz 1987) is an excellent demonstration of how an individual visual observer can improve upon the data available for an RV Tauri star. It is also a good example of the fact that published periods can be far off the mark.

The RV Tauri stars fall between the Cepheids and the Miras not only with regard to period but also in spectral type. At maximum their types are generally F or G (overlapping with the Cepheids), while at minimum they are usually G or early K — decidedly earlier than those of Miras. It is interesting, however, that an RV Tauri star is capable of having two spectral types at once: while the atomic lines indicate a type of late G or early K, the TiO bands may indicate a type of M2 or later. This pecularity is discussed further below (§4).

We should probably include a late-type spectrum as part of the definition of an RV Tauri star. If we require only that the light curve have a period between 30 and 150 days with a tendency toward alternating deep and shallow minima, stars of a completely different physical nature might occasionally qualify for inclusion in the class. Recently we obtained the spectrum of HQ Mon, which had been catalogued as a possible RV Tauri star in the General Catalogue of Variable Stars (Kukarkin _et al_. 1969; hereafter GCVS), and we found it to be a peculiar B-type star with emission lines, possibly a cataclysmic variable (Wahlgren _et al_. 1985).

Wahlgren (1986) has pointed out that there are only 104 stars classified as RV Tauri stars in the GCVS, and that several of these — like HQ Mon — have probably been misclassified. Thus the RV Tauri stars are one of the rarest kinds of intrinsic variables, and it is not unreasonable for an observer to consider observing all of them.

In the hope of encouraging better coverage of the RV Tauri stars by visual observers, I have listed in Table I the 25 brightest members of the class. This short list contains one-quarter of all known RV Tauri stars and includes all that reach magnitudes brighter than 10.0, at least occasionally. The three stars at the top of the list — R Sct, U Mon, and AC Her — are usually well observed by AAVSO members, but relatively few observations are reported for the remainder. Note that the prototype of the class, RV Tau, is fairly far down on the list; it is usually found between magnitudes 9 and 11.

On HR diagrams, the region occupied by RV Tauri stars is often indicated as a small area just to the right of the Cepheid instability strip. It should be pointed out, however, that we really have very little hard information about their absolute magnitudes, or the range in absolute magnitude among members of the class. When RV Tauri stars have been classified on the MK system, they have usually been called Ib supergiants; on the other hand, the atomic-line ratios used to indicate luminosity class are also sensitive to physical effects such as stratification and turbulence, and as a result it is not uncommon for variable stars to appear spectroscopically to be more luminous than they really are.

A few RV Tauri stars do have well-determined absolute magnitudes, namely the ones that belong to globular clusters (Joy 1949), and these stars do appear to be luminous enough to be called supergiants. On cluster color-magnitude diagrams they fall in no-man's land above the horizontal branch and somewhat to the left of the asymptotic giant branch; they are, in any case, among the brightest stars of their respective clusters. Unfortunately, these cluster members are all quite faint and are hard to compare spectroscopically to the brighter field variables.

The occurrence of RV Tauri stars in old globular clusters is proof that at least some of these variables are old, low-mass objects: they must be as old as the clusters they are in, and if their main-sequence mass had been greater than about 1 solar mass their evolution would by now have progressed to the white dwarf stage. But it does not follow from this that all RV Tauri stars belong to old Population II or are low-mass objects.

An important spectroscopic and photometric study of the RV Tauri stars was carried out at Lick Observatory by Preston et al. (1963) and led to their subdivision into three spectroscopically-defined groups designated A, B, and C. Members of group A, such as R Sct, are relatively strong-lined and sometimes show TiO bands near minimum light. The group C stars, by contrast, have very weak metallic lines and frequently have large radial velocities. The implication is that the stars of group A belong to a younger, more metal-rich, population than the variables of group C. Actual metallicities were not determined, however. Also, it has not been clear whether the two groups have the same mean absolute magnitude.

Group B of Preston et al. (1963) is reserved for those rare variables like AC Her which show enhanced absorption bands of CN and CH. These stars appear to have altered abundances of carbon, nitrogen, and oxygen in their atmospheres; evidently their surface gases have been mixed with material that has been processed by energy-producing nuclear reactions in their interiors. Again, it is not known how these stars compare to those of groups A and B with regard to the elusive but important parameters such as mass, age, and absolute magnitude.

3. The Metallicities of RV Tauri Stars

As I have tried to indicate, the basic properties of the RV Tauri stars are still not well known, and in particular there are questions concerning the evolutionary status and absolute magnitudes of the various sub-groups.

The chemical composition of a star — in particular its "metallicity", i.e. its richness in elements heavier than helium — is often a useful clue to its age or population type. There have been indications that the metal abundances of RV Tauri stars cover a substantial range, but few actual determinations of metallicity have been available. The metallicity of a star reflects the composition of the interstellar cloud from which it formed, and it gives an idea of the star's age because the interstellar medium has become progressively richer in metals throughout the history of the Galaxy. The correlation between metallicity and age is not perfect — stars having roughly the solar composition can have any age less than about 10 billion years — but at least we can say, I think, that stars which are metal-poor must be at least 10 billion years old (i.e. twice as old as the Sun).

A major spectroscopic study of the RV Tauri stars has recently been carried out at the Ohio State University as the Ph.D. dissertation of Glenn Wahlgren (1986). He obtained medium-resolution spectra for more than 20 RV Tauri stars with the OSU image-dissector scanner on the Perkins 72-inch telescope in Flagstaff. Analyzing the spectra with the help of model atmospheres and photoelectric color measurements, he derived temperatures, luminosities, and metallicities for most of these stars.

Prior to Wahlgren's work, abundance analyses had been carried out for only three RV Tauri stars — not surprisingly the three stars at the top of Table I. Luck (1981) found that R Sct is deficient in iron-peak elements by nearly a factor of 10, and that the heavier s-process elements are even more deficient. Baird (1981) found AC Her to be metal-deficient by a factor of 16, but with carbon deficient by only a factor of 5. U Mon was analyzed some time ago by Aliev (1965, 1967) but should be reexamined with the help of modern techniques.

Two of Wahlgren's spectra in the blue region, both of the star TT Oph, are shown in Figure 3. Apart from an overall change in magnitude by about $0^{m}_{.}7$, the most noticeable change is in the hydrogen lines which go from absorption to emission. Hydrogen emission was observed in several RV Tauri stars (Wahlgren, Wing, and White 1984) but it is short-lived, usually occurring during the steep rise following a primary minimum.

To analyze the spectra, Wahlgren calculated synthetic spectra from atmospheric models in selected spectral intervals for which he had reasonably complete line lists. The model parameters — temperature, gravity, turbulent velocity, and metallicity — were adjusted until the best fit with the observed spectrum was obtained. The models, which were generated with the code of Gustafsson et al. (1975), are known to represent normal stellar atmospheres very well, but they are static models, not models of pulsating variables. Furthermore, the calculation ignores certain complications, such as sphericity effects, which may be more important in RV Tauri stars than in normal giants. We knew in advance that some of the observed properties of RV Tauri stars could not be reproduced by this family of models, no matter how the parameters were manipulated. For example, it is impossible for the spectrum of one of these models to show detectable TiO bands when the photospheric temperature is that of a G star, as required by the observed color and atomic line strengths; to do so requires a different sort of atmospheric structure, in which there is a substantial amount of relatively cool gas well above the photosphere.

Since a variable star's chemical composition does not vary with phase, one can in principle use observations at any phase for the analysis. But because of the problems mentioned above, we cannot expect to get the right answer if the model does not correctly describe the atmosphere. Wahlgren made the reasonable assumption that a variable star is best represented by a static model at the phases when its spectrum "looks normal" — i.e. when it does not show characteristics that cannot be reproduced in the synthetic spectrum. He therefore excluded spectra showing either TiO bands or hydrogen emission lines from his abundance analysis, thereby avoiding the gross stratification effects that occur near minimum and the rapidly-changing conditions that occur during rising light.

The 19 stars analyzed for metallicity by Wahlgren (1986) were all found to be metal-deficient relative to the Sun, but by widely differing amounts: their iron/hydrogen ratios range from 2 to 50 times lower than the Sun's. The majority of these field stars are within a factor of 10 of the solar metallicity.

It now seems safe to conclude that all RV Tauri stars, including the strong-lined variables of group A, are significantly older than the Sun. However, it appears that most of the field RV Tauri stars should be associated with the Old Disk population, and that only a minority of them belong with the cluster variables in extreme Population II.

An interesting sidelight on Wahlgren's metallicity determinations is the distribution of absolute magnitudes he inferred from the spectroscopically-determined gravities. It would appear from this work that most field RV Tauri stars are 1 - 2 magnitudes less luminous than the variables in globular clusters. Once again the cluster variables seem to occupy one end of a fairly broad distribution.

4. **The Behavior of TiO in R Scuti**

R Scuti is the brightest RV Tauri star and also the best example of a variable with anomalously strong TiO bands at minimum light. Measurable TiO bands appear at most of its minima, even ones that are not particularly deep, but during most of the cycle the bands are absent. The spectral type judged from atomic lines is usually in the G's and is never observed to be later than early K, even at deep minima; on this basis one would not expect to see TiO absorption at all.

The anomalous behavior of TiO in R Sct has been recognized for half a century. During the 1930's, Dean McLaughlin of the University of Michigan made extensive spectroscopic observations of R Sct, recording spectral types and radial velocities. In Figure 4, which is based on a figure by Payne-Gaposchkin *et al*. (1943), the Michigan types for a 600-day interval in 1932-33 are plotted on the AAVSO light curve. The atomic-line types, shown above the curve, range from G0 to K0 and are clearly correlated with magnitude. Whenever TiO was seen, a second type based on TiO strength was recorded and is shown below the curve. Following the usual convention for classifying M stars, the numerical subdivisions of class M are simply indices of TiO strength with type M0 corresponding to the first appearance of the bands on low-dispersion plates. We see that spectral types M0 and M1 occur rather commonly whereas types later than M2 are encountered only at deep minima.

If the spectral types are interpreted in terms of temperature in the usual manner, the types based on TiO indicate temperatures approximately 1500 K lower than do the atomic-line types. It seems clear that the TiO bands are formed not in the photosphere but in a much cooler region well above it. On the other hand the cool region cannot be completely detached, as in a circumstellar shell, since then the band strengths would be the same at all phases. So we picture R Sct as having a greatly extended atmosphere, in which the cool upper layers are loosely attached to the photosphere.

Careful observations of TiO band strengths in RV Tauri stars may thus help to tell us the structure of their outer layers — which, as we have seen, cannot be described in terms of the grid of model atmospheres developed to describe normal, static giants. In particular it would be interesting to observe the rate at which the band intensity changes in response to changes in the photospheric temperature. Surprisingly, since the early work shown in Figure 4, almost no spectroscopic monitoring of RV Tauri stars has been done, although scattered observations of anomalous TiO strengths have been reported for several members of the class.

Since the principal TiO bands have well-defined heads and continuously blanket broad regions of the spectrum, quantitative measures of TiO strength can be obtained easily and accurately by narrow-band photometry. A pair of interference filters having widths of 50 - 100 Å, appropriately positioned in the spectrum and mounted in a photoelectric photometer, is all that is really needed. I have been measuring TiO bands in a slightly more complicated way, with a set of eight filters in the near infrared that also measures the color temperature and bands of VO and CN (Wing 1971). The system is very sensitive to the presence of TiO, and the bands can be measured in stars as early as type K3.5. The classifications obtained for M stars in this way have high internal precision, so that the spectral types can be finely subdivided.

Observations on my eight-color system would be ideal for following the behavior of TiO in RV Tauri stars, but their periods of 2-4 months make these stars awkward objects for professional astronomers, who often live far from their telescopes and have to compete for telescope time. This same property, of course, should make them prime targets for small college observatories and for individuals with telescopes in their back yard.

In August 1985, R Sct experienced one of its deepest minima ever recorded. At the time I was at Cerro Tololo Inter-American Observatory in Chile, doing eight-color photometry of M giants in a field centered on the South Galactic Pole. At that time of year the nights are long and the region of the galactic cap does not get high enough for photometry until midnight. That left me with time to observe other objects, and I was able to include quite a few RV Tauri stars at random phases. Only one of them — R Sct — had detectable TiO bands, but it more than made up for the others by showing bands of record-breaking strength, corresponding to spectral type M5.3. Only once before had this star been seen to reach a type as late as M5, at the deep minimum of July 1932 shown in Figure 4.

One of the pleasant aspects of observing at the national centers is the interaction with other astronomers who are there to use the other telescopes. The advantages are not merely social: at the dinner table one may hear of discoveries made the preceding night and may thus be able to make timely follow-up observations. In this case, after finding R Sct to have such strong bands, I appealed to my colleagues to help document the event. Ex-AAVSOer Brad Schaefer, on Cerro Tololo to try to detect flashes from gamma-ray bursters, used binoculars to estimate the magnitude as 7.9, far outside the range given in Table I; as I have subsequently learned, other AAVSO data confirm his estimate and show that minimum light had actually occurred two weeks before, at magnitude 8.4. And G. Fontaine and F. Wesemael of the Université de Montréal took spectra of R Sct and comparison stars on each of the next several nights. Since they were using the 1.5-m telescope to study the spectra of 16th-magnitude white dwarfs, I was a bit concerned that an 8th-magnitude RV Tauri star might damage their detector, but they found they could obtain very nice spectra of R Sct with an exposure time of 0.4 second!

One of the spectra of R Sct obtained by Fontaine and Wesemael, reduced to a scale of absolute fluxes, is shown in Figure 5 along with the spectrum of AA Scl, a typical M giant. Nearly all the absorption in both spectra is due to TiO, and the two stars have rather similar TiO strengths: according to eight-color photometry obtained on the same night, AA Scl was at type M4.5 and R Sct at type M5.3. Their colors, however, are grossly different: AA Scl has the expected energy distribution for an M5 giant with an effective temperature of 3000 - 3500 K, while R Sct has the color of a G star with a temperature closer to 5000 K. Here we have confirmation that the photosphere of R Sct is as hot as the atomic lines have been telling us, the TiO band strength notwithstanding.

My observing run in Chile was not long enough to show significant changes in the TiO bands of R Sct, but Wahlgren and I were able to continue coverage for six weeks with our "backyard" telescope, the 32-inch reflector at Perkins Observatory (Wing et al. 1985). We used only two filters — the TiO filter centered at 7120 Å and a continuum filter at 7540 Å — but this was enough to monitor the change in TiO strength as the star brightened. The bands weakened but — remarkably — did not go away, even when the star reached maximum light. This is, we believe, the first time the TiO bands in R Sct have been seen at maximum. Evidently the preceding deep minimum produced such a large quantity of TiO in layers so far above the photosphere that not all of it was dissociated the next time the photosphere heated up.

Many more observations of the type described here are needed to clarify the relation between the photosphere and the layer in which the TiO bands are formed. The point that should be made is that these observations are very simple for anyone with a small telescope and a photometer. Here we have a bright star behaving in a way that surprises us because no one has adequately monitored the changes in its TiO bands.

Persha (1987) has described a set of three filters which can be mounted in an Optec solid-state photometer to obtain much of the same information as I do with my eight-color system. Two of the filters provide an index of the TiO absorption near 7100 Å, and the third filter at 10400 Å gives a long baseline for color measurements. I have recommended the use of this simple three-color system for studies of Mira variables (Wing 1987), and here I would just like to add that the same technique could provide important data for the brighter RV Tauri stars.

Light curves, whether determined visually or by some other technique, form the backbone of variable-star studies, and certainly one of the purposes of this paper is to encourage better coverage of the RV Tauri stars by visual observers. But for observers with photometers and an inclination to measure something more than a light curve, I would recommend using a filter set like the one described by Persha (1987) to measure both a color index and a TiO index. The observations themselves are then somewhat more complex than simple magnitude measurements, but they have the distinct advantage that we may one day be able to interpret them!

5. Acknowledgements

This paper owes much to Glenn Wahlgren, and I thank him for the opportunity to look over his shoulder as he carried out his thesis research (not that he had any choice). I also thank the staff of Cerro Tololo Inter-American Observatory, where the observations of R Sct described in §4 were made, for making available their fine facilities.

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TABLE I

The 25 Brightest RV Tauri Stars

Name	Approximate Range in Visual Magnitude	Period (days)
R Sct	4.9 - 6.9	140.2
U Mon	5.1 - 7.1	92.26
AC Her	6.4 - 8.7	75.4619
IW Car	6.9 - 8.6	67.5
AR Pup	7.7 - 9.9	75.
V Vul	8.1 - 9.4	75.72
AR Sgr	8.1 - 12.5	87.87
RU Cen	8.2 - 9.7	64.727
RY Ara	8.2 - 11.1	143.5
SS Gem	8.3 - 9.7	89.31
R Sge	8.5 - 10.5	70.594
AI Sco	8.5 - 11.7	71.0
SX Cen	8.6 - 11.5	32.8642
TX Oph	8.8 - 11.1	135.
RV Tau	8.8 - 12.3	76.698
UZ Oph	9.2 - 11.8	87.44
DY Aql	9.2 - 11.9	131.42
DS Aqr	9.3 - 10.6	78.30
TW Cam	9.4 - 10.5	85.6
TT Oph	9.4 - 11.2	61.08
EP Lyr	9.6 - 10.9	83.315
UY CMa	9.8 - 11.8	113.9
DF Cyg	9.8 - 14.2	49.8080
CT Ori *	9.9 - 11.2	*135.52
SU Gem	9.9 - 12.2	50.12

Based on data in the 3rd edition of the GCVS (Kukarkin et al. 1969). A color index B-V = $1^{\mathrm{m}}0$ has been assumed whenever a photographic or blue magnitude is given in the GCVS.

*CT Ori: A revised period is given by Horowitz (1987).

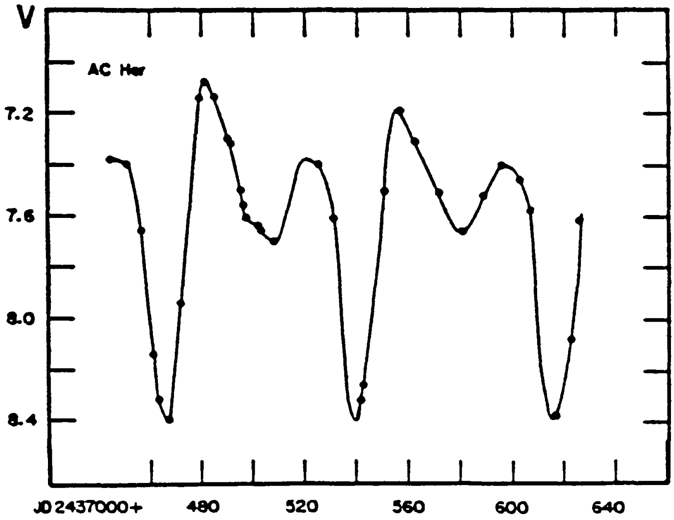

Figure 1. Photoelectric measurements of the V magnitude of AC Her. During this six-month stretch in 1961, the deep and shallow minima alternated with great regularity. After Preston et al. (1963).

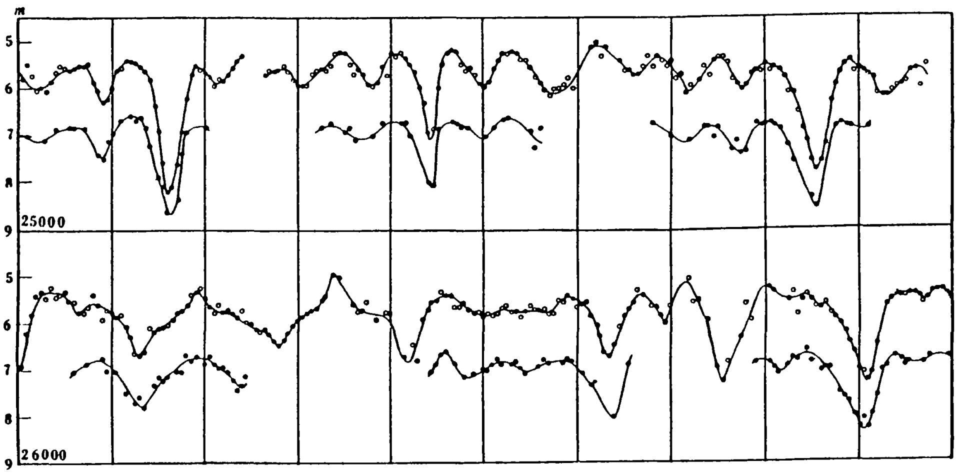

Figure 2. Visual and photographic light curves for R Sct from 1927 to 1932. Each box represents a time interval of 100 days. The visual (upper) curve is based on AAVSO data, while the photographic curve was obtained from Harvard plates (Payne-Gaposchkin <u>et al</u>. 1943).

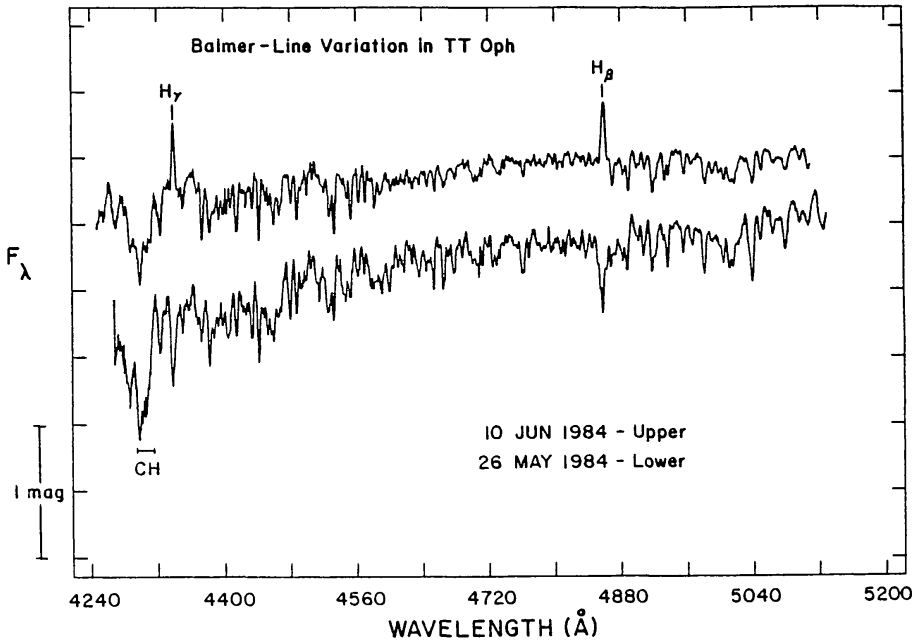

Figure 3. Two spectra of TT Oph in the blue region, separated by an interval of 15 days. As the star brightened, its hydrogen lines of the Balmer series changed from absorption to emission. The strong absorption feature at the left is the G band of CH. From a poster presentation by Wahlgren, Wing, and White (1984).

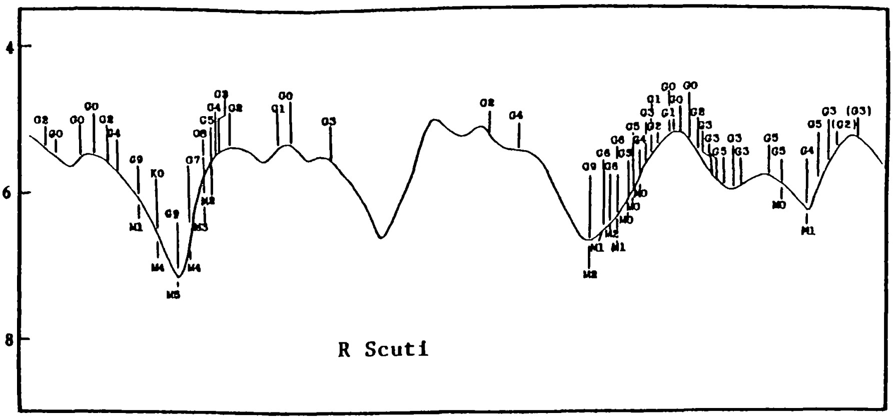

Figure 4. Spectral types for R Sct based on atomic lines (above curve) and TiO bands (below), plotted on the AAVSO light curve for the interval JD 2426800 - 2427400. From a figure by Payne-Gaposchkin *et al*. (1943).

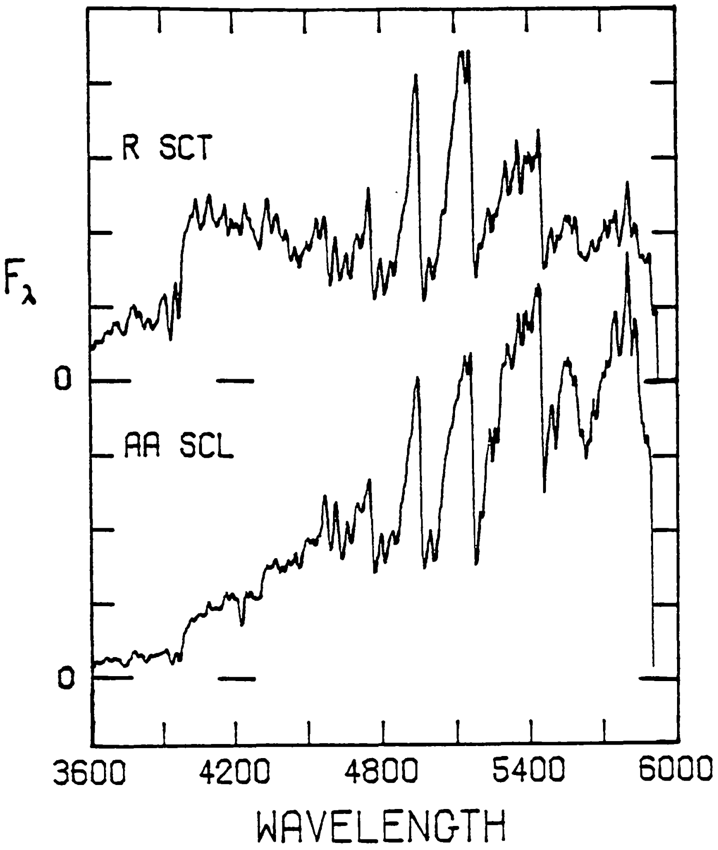

Figure 5. Comparison of the spectra of R Sct, an RV Tauri star near minimum, and AA Scl, an M giant, in the blue and yellow regions. The spectra, which were obtained by G. Fontaine and F. Wesemael with the SIT vidicon spectrograph on the 1.5-m telescope on Cerro Tololo, have been reduced to a scale of absolute fluxes (i.e. the instrumental sensitivity function has been removed). Nearly all the absorption is due to TiO in both stars. Note that R Sct is much bluer than AA Scl, despite their similar TiO band strengths. See Wing *et al*. (1985).