The Spectra of Novae

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SUMMARY

Typical novae have four systems of absorption lines. In chronological order of appearance, as well as of increasing displacement, these are: (1) pre-maximum; (2) principal; (3) diffuse enhanced; (4) Orion. The principal system lies on the short wavelength edges of a strong set of wide, undisplaced emission lines. Structures appear early in the emission and can be correlated with local knots in the expanding nebulae years later. Diffuse enhanced and Orion lines also have associated, but more vague, emission.

Secondary variations of light are correlated with spectral changes. With a re-brightening, the spectrum reverts to a stage already passed. Variations of line displacements accompany these changes. For Orion lines the oscillations are considered real, and due to variable speed of ejection. In the diffuse enhanced system, apparent oscillations are due mainly to variable strength of blended, multiple lines. Critical examination fails to confirm supposed rapid gravitational retardation of gases.

Recurrent novae form a special problem. Some, at least, fail to fit the typical pattern. Old novae, and probably pre-nova stars as well, are hot subdwarfs.

1. INTRODUCTION: VARIATION OF LIGHT

IT is a little more than sixty years since the first photographs were obtained of the spectrum of a nova. Since that date, approximately 100 novae have been discovered, and for about half of these, at least one spectrogram has been obtained. The record can be called extensive for fifteen stars. This material appears sufficient to justify attempts at generalization on such matters as the typical course of development and relationships between the light variations and spectral changes.

The rate of brightening is unknown in a majority of novae. All positive observations agree in showing a rise from minimum to within a few magnitudes of maximum in only two or three days, except for such ultra-slow objects as FU Orionis. After this initial rise, differences in rate of change are evident. The fast novae reach maximum in another day or so; the slow require several days to several weeks. The subsequent decline is slower than the rise, save for occasional sudden fading associated with irregular fluctuations. Such irregularities during the first week or two of the decline are rare in fast novae, but are almost (though not quite) universal among slow novae. Durations of decline through three magnitudes range from two weeks for fast novae to a few months for slow ones. After the star has faded about four magnitudes, there is commonly a more or less prominent minimum of light, followed by a recovery. Alternatively, this feature may take the form of a marked decrease of slope or constancy of the light curve. In the Nova Herculis type the minimum is several magnitudes in depth. A few of the fast novae in this "transition" stage undergo sub-periodic fluctuations with cycles several days in length. At six or seven magnitudes below maximum, the oscillations cease, and the remainder of the decline is uneventful.

2. EARLY STAGES OF NOVA SPECTRA

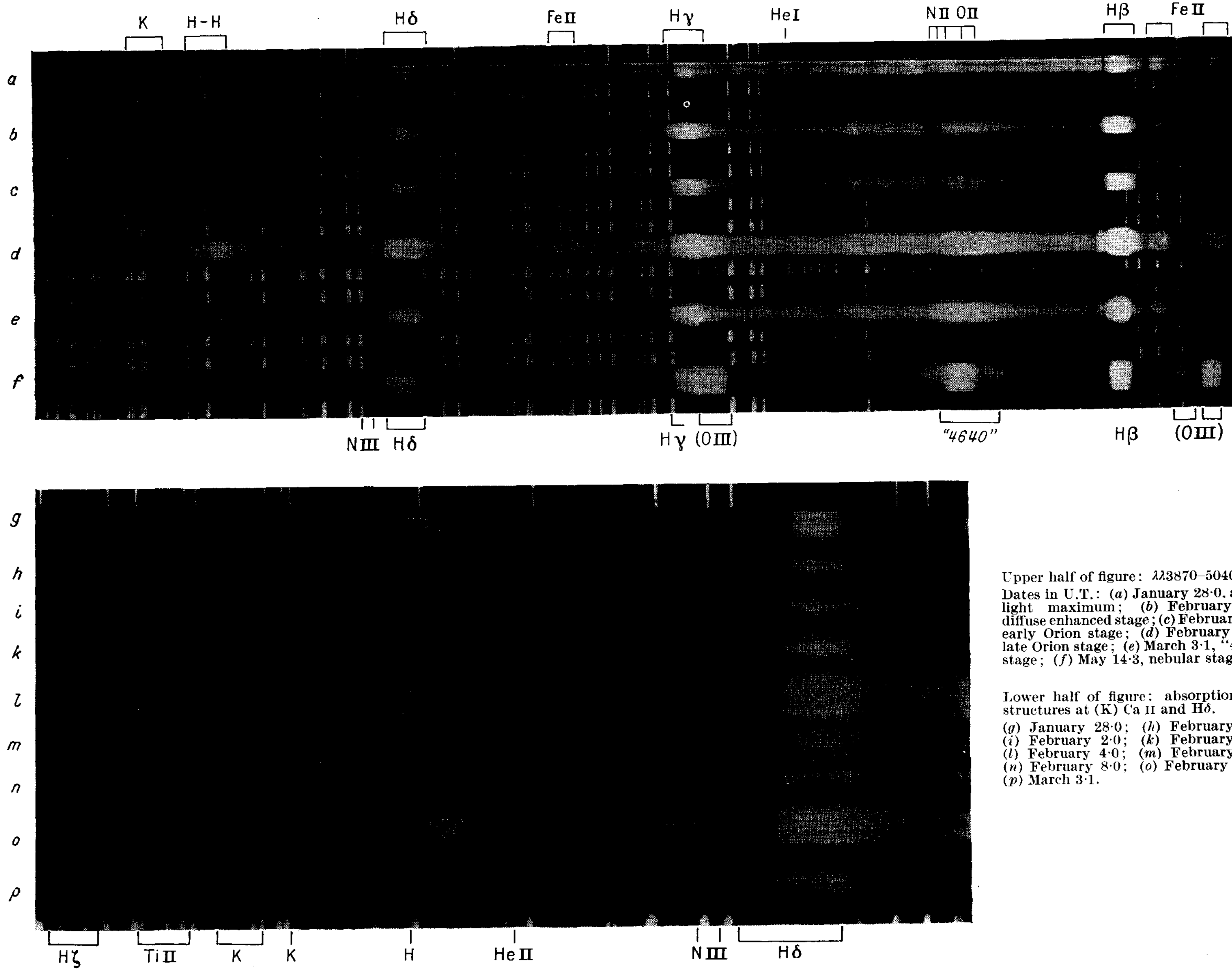
The spectroscopic record is now sufficiently extensive to warrant the belief that the spectra of only two major stages remain unknown. These are the quiescent pre-nova star and the rapidly brightening nova in its early phase. The equal luminosity of pre- and post-nova stars, combined with the similarity of recurrent and typical novae at minimum, even furnish good ground for belief that we do know something of the pre-outburst stage, but this view is not unassailable. The only extant record of a pre-nova spectrum, that of Nova Aquilae 1918, is faint and difficult of interpretation (CANNON, 1920).

The earliest spectroscopically recorded stage is about two magnitudes below maximum on the rise. Several stars have been caught at this time—Nova Herculis probably earliest. Three had absorption spectra of class B, and Nova Herculis was remarkable for its strong emission lines (STRATTON, 1936b, p. 133) in contrast to their weakness in other stars. Nearly all novae for which the record is adequate have changed towards "later" spectral type as maximum was approached. Nova Herculis changed from B to F; several have changed from early to late class A or early F. But especially remarkable is the absolute intensification of absorption, quite apart from relative changes associated with spectral class. Apparently we witness a transformation of the atmosphere from one of ordinary extent to one like that of a supergiant star. The "photosphere" is simply an optical level in the growing cloud, and the growth of this "surface" is much less rapid than the observed velocities of absorbing atoms would indicate (BEER, 1937). Material continually emerges from sub-photospheric to super-photospheric levels as the cloud expands, and the depth of the absorbing atmosphere therefore increases steadily.

The typical sequence of events in a nova spectrum is now so well known that we need not describe it in great detail. Fig. 1 illustrates several stages of Nova DK Lacertae 1950. At maximum light the "pre-maximum" absorption spectrum is still dominant. It resembles that of a supergiant star, such as α Cygni or ε Aurigae, and it is more or less strongly displaced towards shorter wavelengths. Emission is rarely present and never strong. Very soon after maximum (usually before the star has faded more than 0·5 magnitude) the pre-maximum spectrum is replaced by a quite similar one, the "principal spectrum". Its shift towards the violet considerably exceeds that of its predecessor. Where adequate observations are closely spaced, as in RR Pictoris 1925 (JONES, 1931, p. 35) and in DQ Herculis 1934 (MERRILL, 1935; STRATTON, 1936b, p. 148), the two spectra have been observed simultaneously for a day or two. The new spectrum emerges as the old one fades, but the similarity is so close that, if we lacked observations at the crucial stage, we might conclude that a single set of lines had abruptly shifted position. With the emergence of the principal absorption, bright bands develop. The strongest are due to hydrogen, Ca II, and Fe II. Their centres are approximately undisplaced, and the absorption lines lie upon their shortward edges. This structure points to an ejection of matter that roughly approximates spherical symmetry, though the later development of the bands reveals conspicuous irregularities of density.

3. INTERMEDIATE STAGES

In following stages, two more absorption systems commonly become conspicuous. These have been called the "diffuse enhanced" and "Orion" spectra. The former is at its strongest about two magnitudes below maximum. It consists of strong and diffuse lines of hydrogen, Ca II, Fe II, and usually O I and Na I; in some slow novae it has contained lines of Ti II and Cr II as well. Its velocity is roughly double that of the principal spectrum. The Orion system reaches greatest strength somewhat



Upper half of figure: $\lambda\lambda$3870–5040.
Dates in U.T.: (*a*) January 28·0, about light maximum; (*b*) February 3·0, diffuse enhanced stage; (*c*) February 5·0, early Orion stage; (*d*) February 18·0, late Orion stage; (*e*) March 3·1, "4640" stage; (*f*) May 14·3, nebular stage.

Lower half of figure: absorption line structures at (K) Ca II and Hδ.
(*g*) January 28·0; (*h*) February 1·1; (*i*) February 2·0; (*k*) February 3·0; (*l*) February 4·0; (*m*) February 5·0; (*n*) February 8·0; (*o*) February 18·0; (*p*) March 3·1.

Fig. 1. Spectra of Nova DK Lacertae 1950
Taken at the University of Michigan Observatory.

less than three magnitudes below maximum. Its most conspicuous lines are those of He I, O II, and N II. Hydrogen appears to be a rather variable constituent and was probably absent in a few cases, notably in Nova Herculis. The velocity is usually close to that of the diffuse enhanced absorption, but slightly greater numerically. Occasionally it is much greater; rarely it is less.

Emission is associated with both diffuse enhanced and Orion absorptions. The centres of the widened bright lines are essentially undisplaced, with the absorption lying at the shortward edges. The diffuse enhanced emission has moderately well-defined edges, but the "Orion" is commonly very hazy. Both lack internal structure and seem to be produced in material that is ejected nearly equally in all directions, probably with a considerable spread of velocities.

As the lines of the diffuse enhanced absorption weaken, they separate into several narrow lines, and even near the time of maximum strength some suggestion of resolution may be visible. The Orion absorption, on the other hand, is single but its lines are usually diffuse. As the lines of He I, N II, and O II fade, absorption lines of N III become strong near Hδ and a broad hazy emission of N III strengthens at "4640". A few novae have had vague absorption attributed to N V, which appeared as the N III lines faded in their turn.

4. Nebular and Later Stages

The changes just described show a sequence of increasing excitation as the nova fades. The principal emission spectrum exhibits a similar trend. He I, C II, and N II lines emerge, followed later by N III and He II. The resemblance of their structures to those of the hydrogen lines identifies them surely as members of the principal emission. By the time the star has declined five magnitudes, the nebular lines of [O III] have become conspicuous and all absorption systems have disappeared. The remaining emission spectrum resembles that of a planetary nebula, except for the widths of the lines.

Some of the nebulae that have been seen to expand about novae have been observed spectroscopically. Always their spectroscopic cross-sections show Doppler ellipses or fragments thereof, whose widths along the dispersion identify them with the principal spectrum and no other. In Nova Aquilae 1918 (W. Baade, personal communication; see van de Hulst, 1951) and Nova Persei 1901 (Stratton, 1936a), certain knots in the nebulae could be correlated with maxima that appeared in the emission bands within less than a week after light maximum and persisted thereafter with only minor changes of position (Pearson, 1936). Such continuity of structure seems to be the rule. Its early appearance and its persistence can only mean that the principal shell was ejected violently and within a short interval—possibly within a few hours.

During the few years that follow the emergence of the nebular lines, the emission spectrum of the shell fades more rapidly than the central star, until only the stellar spectrum can be recorded at all. In this stage the star, still one or two magnitudes above minimum, has a continuous spectrum with great extent in the violet and usually with superimposed bright lines of hydrogen and He II several Ångstroms wide. As Nova Aquilae 1918 faded through the last two magnitudes, its hydrogen lines strengthened relatively to He II, suggesting that the end of the decline was accompanied by a lowering of temperature. Some novae have bright lines for many years after reaching minimum, while others have purely continuous spectra

(HUMASON, 1938). Possibly all eventually lose their bright lines, but if so, the process must take decades in some cases. It is probably no mere coincidence that Nova Persei 1901, whose bright lines outshone those of other known old novae, is the most outstanding example of continued variation.

5. STRUCTURE OF NOVA SHELLS

The evidence for the association of the principal spectrum with the main ejected cloud is fairly direct. The locations of origin of the diffuse enhanced and Orion spectra have to be inferred from evidence of a more circumstantial character. Nearness to or remoteness from the star may be judged from response to light variations, by relative level of excitation, and by evidence of dilution of radiation. Position inside or outside of any emitting or absorbing layer may be indicated by superposition of spectral features. Thus, both principal and diffuse enhanced absorption cut hazy N III and other Orion emissions, but principal emission maxima filled in the shifting N III absorption lines of Nova Aquilae 1918 (WYSE, 1939, p. 117). Some lines of Ti II in the diffuse enhanced system of Nova Herculis were obliterated by principal emission of Fe II. The ready response of the Orion spectrum to light variations of the star is well known. The conclusions are (McLAUGHLIN, 1947b): (1) the diffuse enhanced spectrum originates inside the principal shell; (2) the Orion spectrum is produced close about the star, after the clouds responsible for the diffuse enhanced spectrum have detached themselves. The multiplicity of the latter suggests a number of discrete clouds moving outward with different velocities to overtake the principal shell.

The foregoing discussion has been kept fairly general. Individual novae depart more or less from the standard pattern. Some have had only relatively inconspicuous diffuse enhanced spectra (Nova Persei 1901), and in some the Orion spectrum has been extremely weak, if not absent (Nova CP Puppis 1942). In general, these two "secondary" spectra are strongest in the slow novae. Their intensities may be a measure of the ejection that continues after the "main burst", and perhaps it is simply this continuing activity that sustains the brightness of the star for so long a time.

6. CYCLIC VARIATIONS OF SPECTRA

The most interesting of all deviations from the regular course are those connected with secondary fluctuations. In all cases the long-term trend conforms to the standard pattern, while the fluctuations are expressed by what may appropriately be called "STRATTON's Rule". This has been stated by its author as follows:

> ". . . a maximum corresponds to a spectrum which is normal at an earlier stage of the star's history". (STRATTON, 1920.)
>
> ". . . when the star brightens its spectrum returns to that of an earlier and brighter stage, the spectrum being in fact a simple function of the magnitude". (STRATTON, 1928.) See also STRATTON (1936c.)

This rule has been abundantly confirmed by observations of a number of novae. The only known conspicuous exceptions have been associated with the deep minima and recovery in the transition stage of stars of the Nova Herculis type.

Nova Geminorum 1912, RR Pictoris 1925, and V356 Aquilae 1936, to name a few good examples, had correlated fluctuations of magnitude, spectrum, and velocities of absorption systems in the early post-maximum stages. A secondary minimum in the very early decline may be accompanied by strong emergence of the diffuse enhanced spectrum which will weaken again as the star recovers. Farther down the decline, a fading of the star may be correlated with weakening of the diffuse enhanced and emergence of a strong Orion spectrum. A re-brightening will then resuscitate the diffuse enhanced and erase the Orion lines. Still later both systems may be weak at a secondary minimum and both may be strengthened at a subsequent maximum.

Fluctuations during the transition stage, such as those of Nova Aquilae 1918, Nova Persei 1901 and Nova Geminorum 1912 involve the appearance of nebular emissions at light minima and their disappearance at maxima, as well as "nitrogen flaring" at the maxima.

In the oscillations, both absorption and emission change in a way that indicates higher excitation at light minima and lowest at the maxima. The few available measures of energy distribution in the continuum yield highest colour temperatures at the minima (Beileke and Hachenberg, 1935). These correlations become understandable if we regard the maxima as secondary outbursts, in which newly ejected material forms an effectively larger but cooler "photosphere" about the star. In this cloud most of the high frequency radiation is absorbed, leaving little for excitation of the outer gases. The emission spectrum of the principal shell, coming as it does from the outermost gas, is particularly susceptible to these effects. Such changes were illustrated beautifully by Nova Geminorum 1912, in which He I emission was strong at the minima, but was outshone by Na I at the maxima. In the novae that showed nitrogen flaring, the "4640" region was occupied during light minima by definite bands due to N III and He II that had the structure of the principal emission. These were obliterated at the maxima when N III flared (Wright, 1926). The re-appearance of the same structure at following minima rules out mechanical destruction of the source of the principal bands. The variation must have been an excitation effect. It is attributed to extinction of high-frequency radiation in the newly ejected clouds at times of light maxima.

When the variations are fairly regular, we may question whether the correlation is influenced by relaxation time. A lag of half a period would mean that the star was hottest at the maxima. However, it is unlikely that the densities could be so low as to introduce a lag of some days. An observational decision was rendered by Nova Geminorum 1912, whose secondary variations were rather irregular. The coincidence of low excitation with the maxima was faithfully adhered to. It must be concluded that relaxation times were short compared with the length of a cycle.

7. Radial Velocities of Absorption Systems

The velocities of all absorption systems are somewhat variable. Too little is known of the pre-maximum spectrum to permit generalization. In Nova Herculis its velocity decreased (numerically) from more than 1000 km per sec (with enormous systematic differences between lines) to about 175 km per sec (Stratton, 1936b, p. 133). Nearly all the principal spectra that have been observed over an interval of weeks have shown a tendency to increase in velocity. The acceleration was very small in Nova Geminorum 1912, but in Nova Lacertae 1936 the velocity changed from -1300 to -2500 km per sec in two weeks.

Oscillations of the Orion lines are usually related to changes of magnitude. At light minima the displacements are (numerically) greatest; they are least somewhat before the maxima. The N III lines, survivors of the Orion system, displayed these changes to a spectacular degree in Nova Aquilae 1918 (WYSE, 1939, p. 115). But in some stars, notably Nova CP Lacertae 1936 and V528 Aquilae 1945, large oscillations of Orion lines have occurred without distinct fluctuations of light.

The diffuse enhanced absorption lines in slow novae behave in a complicated manner. Often the relationship of velocity of the broad blend to magnitude of the star is similar to that of the Orion lines. Critical examination shows that these apparent variations of velocity may plausibly be attributed to changes of strength of components of the blend. This was certainly true in some novae, especially in RR Pictoris 1925 (JONES, 1931, p. 19). We must be on our guard against interpreting variations of measured position too literally in terms of acceleration or deceleration of discrete bodies of gas.

Only of the principal spectrum can we say with some confidence that we deal with a discrete cloud that retains its identity for a large fraction of the nova's history. This conclusion is justified by the observations of the growing nebulosity. The increase of velocity of the principal absorption is most reasonably interpreted as an actual acceleration. The hypothesis of a discrete expanding shell finds remarkable confirmation in the concentration of atoms in metastable states as the incident stellar radiation becomes more and more dilute at great distances from the star (STRUVE, 1939).

The oscillations of the Orion lines cannot be seriously regarded as a result of acceleration and deceleration of a discrete cloud. Rather, at different times the atoms that are streaming through the region where Orion lines originate are moving with different speeds. The apparent continuity of the Orion spectrum must be viewed as an example of P Cygni-like ejection and renewal.

Variations of velocity of diffuse enhanced lines have been discussed already. When components are well resolved they have nearly constant or only slowly changing velocities. One or two marked exceptions have been observed; for example, a single component in RR Pictoris (JONES, 1931, p. 19) shifted rapidly towards smaller displacement, while others remained nearly fixed. This behaviour is tentatively considered as an example of retardation by another shell of gas—in this specific case the principal shell.

There is no known example of a demonstrable large *gravitational* deceleration of an absorption component of the principal, diffuse enhanced, or Orion systems. Some supposed cases of this sort clearly arose from blends or variable ejection speeds, and most others can reasonably be presumed to have been so produced. None of the supposed gravitational decelerations survive critical examination, and we must regard with suspicion any calculations based upon them, particularly when they lead to stellar masses that can only be described by the adjective "fantastic".

The material ejected in the principal shell is forever lost to the star. It leaves with a velocity well above that of escape (from a star of normal mass). But it may be quite otherwise with some of the later eruptions that occur during the transition stage. At times, when the violently ejected clouds have cleared, we have had fleeting spectroscopic glimpses of the inner star, from which some gases—notably He II—emerge with less than the escape velocity. This gas is evidently slowed to zero velocity, for subsequent brightening has momentarily silhouetted the stationary gases and revealed their presence by undisplaced absorption at λ4686 He II. This occurred several times in Nova Geminorum 1912 (WRIGHT, 1926), perhaps in Nova Persei 1901, and certainly once in T Coronae Borealis (MCLAUGHLIN, 1947a).

When we consider all novae for which reliable data exist, rather definite relations are found between rate of decline of light, velocity of the principal spectrum, and rate of passage through spectral stages. The following expressions were derived empirically (McLaughlin, 1937, 1940):

$$\log_{10} V = 3\cdot19 - 0\cdot54 \log_{10} t_S$$
$$\log_{10} V = 3\cdot22 - 0\cdot50 \log_{10} t_L,$$

where V is the velocity in kilometres per second, t_S the duration of a given spectroscopic change (in an arbitrary unit), and t_L the duration of three magnitudes' decline, in the same arbitrary unit. To sufficient accuracy, it can be said that the duration of a given change of magnitude or spectrum varies inversely as the square of the velocity. Among "non-recurrent" stars only Nova Cygni 1920 and CP Puppis 1942 departed conspicuously from the second equation but not from the first. For these two stars the light variations ran their course more rapidly than the formula would indicate.

8. Recurrent Novae and Other Problems

Recurrent novae are exceptional in many ways. Both T Coronae Borealis and RS Ophiuchi utterly failed to conform to the pattern of absorption systems that characterizes typical novae. In T CrB (Herbig and Neubauer, 1946) vague absorption bordered the violet edges of hazy emission for a few days, but both absorption and vague emission wings disappeared early. Strong narrow emission lines remained at the positions of the band centres. They were flanked on their shortward sides by the most persistent absorption lines, which emerged to view in that position as if they had been simply unveiled. RS Ophiuchi had no appreciable absorption on the band edges, but had instead a sharp absorption of small displacement nearly central on the bands, in addition to a vague absorption that depressed the entire shortward half of the hazy emission (Adams and Joy, 1933; Wilson and Williams, 1934). Both of these stars exhibited much higher excitation than typical novae. This was attested by the great strength of the coronal lines of [Fe X] and [Fe XIV].

Although both showed nebular lines, neither developed a strong "nebular stage". The fragmentary record of T Pyxidis, on the other hand, closely resembled the spectrum of a typical nova, both near maximum (Adams and Joy, 1920) and in the nebular stage (Joy, 1945). In view of the differences, we should be circumspect about attributing to novae in general the characteristics of known recurrent objects. T Pyxidis stands alone in support of the hypothesis of close similarity.

Old novae and, we are inclined to believe, the pre-nova stars also, are bodies of small dimensions and high photospheric temperatures (Humason, 1938). Calculated radii are 0·1–0·2 ⊙, absolute magnitudes + 3 to + 7, and densities probably of order 100–1000 ⊙. On all counts they fall between the main sequence and the white dwarfs, and it is at least permissible to speculate that they are in process of evolution from the former to the latter.

What the mechanism of this evolution may be and, specifically, the immediate cause of an outburst, are the very foremost of the unsolved problems of these stars. The amount of matter lost in an eruption is a minute fraction of a solar mass (Payne-Gaposchkin, 1942), but if all novae recur the loss would be important after several hundred outbursts. Biermann's hypothesis (1939) of a brief change-over from radiative to convective equilibrium may be a step in the right direction.

The future progress of the theory of stellar interiors, rather than presently conceivable observational studies, will aid in the answering of this question.

Numerous problems remain in the interpretation of the changing spectra of the outer gases. To what extent is excitation determined by radiation from the star, as opposed to collisions that occur when one shell overtakes another? At best, any answer would be only tentative in the present state of knowledge. Spectrophotometry is urgently needed, and the more clearly it can be referred to "absolute" standards (such as bright stars with well-determined energy distribution) the more useful it will be for elucidating physical processes. But we still need data of a more prosaic or "old-fashioned" type. It is very doubtful that we shall ever begin to understand what goes on in the erupted material unless we can identify, partly through radial velocity studies, the progress of clouds of gas and especially of shock waves moving through them.

We have only scratched the surface of the nova problem, but perhaps the time is near when we can begin to see beyond the phenomena to the physical reality.

REFERENCES

ADAMS, WALTER S. and JOY, A. H.	1920	*Popular Astron.*, **28**, 514.
	1933	*Publ. Astron. Soc. Pacific*, **45**, 250.
BEER, ARTHUR	1937	*M.N.*, **97**, 231.
BEILEKE, F. and HACHENBERG, O.	1935	*Z. Astrophys.*, **10**, 366.
BIERMANN, L.	1939	*Z. Astrophys.*, **18**, 344.
CANNON, ANNIE J.	1920	*Harvard Annals*, **81**, 179.
HERBIG, G. H. and NEUBAUER, F. J.	1946	*Publ. Astron. Soc. Pacific*, **58**, 196.
HUMASON, MILTON	1938	*Ap. J.*, **88**, 228.
JONES, H. SPENCER	1931	*Annals Cape Obs.*, **10**, part 9, pp. 19, 35.
JOY, A. H.	1945	*Publ. Astron. Soc. Pacific*, **57**, 171.
MCLAUGHLIN, DEAN B.	1947a	*Publ. Astron. Soc. Pacific*, **59**, 84.
	1947b	*Publ. Astron. Soc. Pacific*, **59**, 244.
	1937	*Ap. J.*, **85**, 369.
	1940	*Ap. J.*, **91**, 375.
MERRILL, PAUL W.	1935	*Ap. J.*, **82**, 415.
PAYNE-GAPOSCHKIN, CECILIA and GAPOSCHKIN, SERGEI	1942	*Harvard Circular* 445.
PEARSON, E. S.	1936	*Ann. Solar Phys. Obs.*, Cambridge, **4**, part 3.
STRATTON, F. J. M.	1920	*Ann. Solar Phys. Obs.*, Cambridge, **4**, part 1, p. 65.
	1928	*Handbuch der Astrophysik*, **6**, 279
	1936a	*Ann. Solar Phys. Obs.*, Cambridge, **4**, part 2, p. 84.
	1936b	ibid., **4**, part 4.
	1936c	*Handbuch der Astrophysik*, **7**, 671–684.
STRUVE, OTTO	1939	*Proc. Amer. Philos. Soc.*, **81**, 225.
VAN DE HULST, H. C.	1951	*Problems of Cosmical Aerodynamics*, p. 116. (Central Air Documents Office, Dayton, Ohio, U.S.A.)
WILSON, O. C. and WILLIAMS, E. G.	1934	*Ap. J.*, **80**, 344.
WRIGHT, W. H.	1926	*Lick Obs. Publ.*, **14**, 84.
WYSE, ARTHUR B.	1939	*Lick Obs. Publ.*, **14**, 115, 117.