## ON THE BRIGHT LINE SPECTRUM OF NOVA HERCULIS

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The present paper contains a qualitative interpretation of the main features observed by the authors and by others in the bright line spectrum of Nova Herculis. Like other novæ, Nova Herculis has shown a continuous rise in excitation since it attained maximum; until at the present time (January 29, 1936) it shows a spectrum typical of the so-called "nebular stage." For other novæ this general behavior has been described,[1] and the detailed changes for Nova Herculis need not be discussed here. It may be noted, however, that the forbidden lines of ionized iron, typical of novæ that develop slowly, were observed in the spectrum.[2]

Perhaps the most interesting feature of Nova Herculis is its duplicity, first observed by Kuiper[3] on July 4, 1935. Although this is not the first nova for which apparent multiplicity has been observed,[4] it is of especial interest because of the possibility of identifying the two components with features of the emission spectrum. There can be little doubt that the red and violet components of the doubled emission lines correspond respectively to the fainter and brighter components of the nova observed visually. Before substantiating the statement, we shall trace the history of the two components, as revealed by the bright line spectrum.

An examination of the spectrograms taken at Harvard, and those published by Merrill[5] and by McLaughlin,[6] shows that the bright lines of ionized iron in the green, and other lines excepting hydrogen, first displayed definite duplicity shortly after maximum. The doubling was visible on December 25, and conspicuous on December 26, 1934. Doubling of the bright lines had already been suspected[7] from the Harvard plates of December 20, two days before maximum; but between December 20 and December 25, the contrast shown by the bright lines was so weak, because of the brightness of the continuous background, that their structure was difficult to observe. The lines of hydrogen did not show the effect of duplicity as markedly as the other bright lines until early in March, whereas the forbidden lines of neutral oxygen showed it from their first appearance on December 25, 1934.

Until the middle of March the red component of the doubled bright lines was generally as strong as, or stronger than, the violet component. At about that time it began to weaken, particularly for the forbidden lines [OI]. For hydrogen the effect was delayed until the end of March, being detectable in H$\alpha$ on Bobrovnikoff's spectrum[8] of March 30, and on that of April 2, reproduced by Merrill.[9] By April 5, Wyse[10] states that "all the other emission lines were displaced −400 km./sec., although the strongest ones showed traces of very faint, diffuse components on the red side of the normal positions." This was soon after the beginning of the great drop, which continued until the star had faded to the thirteenth magnitude on about the first of May. Wyse states: "The red components of the hydrogen lines disappeared rather suddenly about the end of April." McLaughlin,[11] describing a series of observations overlapping the previous, states: "As the nova faded, the red components of the emission bands weakened relatively to the violet components. With the subsequent brightening, the violet components alone were seen on May 18, but later the red components appeared and increased toward equality with the violet ones. During July and August the ratio $V/R$ was approximately 1.5, as compared with 5 about June 1."

The nova had repeatedly been examined by Kuiper for duplicity, and was first seen to be double on July 4, with a difference of magnitude[12] of $0.^m4$. If we make the extremely probable assumption that the red and violet components of the bright lines refer respectively to the fainter and brighter components observed visually, we can see why the duplicity could not have been observed earlier. On March 31, April 27 and June 10, 1935, under good seeing conditions, Kuiper examined the nova and found it to be single.[3] On March 31, before the great minimum, the integrated brightness of the continuous background in the photographic region was about half a magnitude greater than that of all the bright lines in that region. In a recent investigation we have shown[13] that most of the light of the continuous spectrum originates in the "photosphere" of the central star. Therefore a star, brighter than the components combined, must have existed between them, and, with so small a separation, would have prevented their discovery. Furthermore, many of the strong double bright lines, notably H$\alpha$, the strongest of them all, had a wide underlying band, of intensity comparable to that of the two components. Thus it is not surprising that the duplicity was not observed on or before March 31. On April 27, as noted by Wyse, the bright lines were almost all single, so that apparently only one component could have been observed. Likewise on June 10, the violet components only were observed by Belorizky,[14] so that only one component could have been seen on that date. During July and August, from McLaughlin's rough estimate of the ratio 1.5 of the violet to the red component in the spectrum, a magni-

tude difference of $0^m.44$ can be computed for the visual components, in close agreement with Kuiper's visual estimate of $0^m.4$. A similar computation for the beginning of June yields a difference of $1^m.75$ between the components, which would have precluded a discovery of the duplicity. The difference of magnitude seems to have persisted with but little change, until October, 1935, according to the observations made by van Biesbroeck.[15]

There can be little doubt as to the nature of the two bodies thus observed visually and spectroscopically. They are not themselves the sources of the energy they radiate, because in the early stages the intensity of their spectral lines follows the irregular changes in brightness of the integrated light of the nova, light which resides mostly in the continuous spectrum. Inspection of the Harvard spectrograms shows that up to the middle of March the bright components of the lines remained practically equal in intensity, both following roughly the fluctuations of the light curve. This result could only be achieved by an indeed remarkable synchronization of two light sources. It seems more likely that the two bodies derive their light from the central star. Their density must be low, because they gave the forbidden lines of neutral oxygen almost from the first; and because they have given a typically nebular spectrum ever since the great minimum, after the continuous background (which we regard as coming mostly from the central star) had faded very considerably. The velocity differences of the two components of the bright lines increased greatly[5,8] between December, 1934 and May, 1935, and apparently a further increase had taken place[10] when the two components appeared again in July, 1935. The finite widths of the bright components can be interpreted as the result of expansion in the discrete masses, the rate of which seems, from Merrill's measures,[5] to have increased somewhat with the time. Both the increasing separation and the increasing width of the lines could be interpreted either as a result of acceleration under radiation pressure[16] or in terms of a change in the effective center of the radiation in the masses, each particle of which is assumed to be moving radially away from the star with a velocity which, for the different particles, is proportional to · the distance. The final choice between these alternatives will depend on the correlation of the acceleration with brightness or with time, after the minimum. The two bodies must therefore be considered to have low density, and therefore probably low mass, and an external source of luminosity. They must have considerable size, because of the very probable expansion indicated by the finite width of the two emission components, and because they must subtend an appreciable solid angle at the star in order to reradiate as large a fraction of its light as they do. The above arguments indicate that the two bodies are in no sense stellar.

The two discrete masses just described must have originated very early

in the outburst, since duplicity of the lines was already suspected before the maximum; and as forbidden lines of neutral oxygen appeared immediately after maximum (indicating that the density of matter and dilution of radiation had already become very low), it is not improbable that the expulsion of these masses from the central star occurred at the very beginning of the rise to the first maximum, and was the immediate result of the disturbance that initiated the nova outburst.   The visual observations of Kuiper and van Biesbroeck indicate that the two masses are separating at a rate not inconsistent with an origin at the star in December, 1934. Since both the radial velocity and the transverse velocity of the components can be observed, they must have been ejected at a considerable angle to the line of sight.

It is clear from a detailed study of the spectra that we are concerned with both absorption and emission from more than one level, as has also been pointed out by Lindblad and Öhman.[17]   In the early stages of the nova we do not consider that the process just discussed is the principal one in the production of the permitted bright lines.   In a previous paper we have discussed observations of the continuous spectrum and (qualitatively) of the absorption lines,[13] and have concluded that the continuous spectrum is produced in the atmosphere of the star, which atmosphere consists of matter continuously ejected from the surface.   In such an atmosphere the absorption lines would be produced at very high levels, and would show velocity shifts corresponding to the speeds with which the atoms flowed outward through the "photosphere."

The permitted and forbidden bright lines must be discussed separately. In all stages of the nova, the forbidden lines can be produced in but two places: in the two discrete masses discussed above; and in the outer portions of the radially symmetrical atmosphere, which may or may not extend as far as the two ejected masses.   Evidence for emission in the forbidden lines from the extended atmosphere is seen in the intensity of the light between the two components of the forbidden bright lines throughout all the early stages of the nova.   Quantitative measures of this intensity in the later stages are not available, but even at that time we may expect that it will be appreciable.   The relative intensities of the light coming from the atmosphere and from the discrete masses should then be a measure of the relative amounts of matter involved.   This ratio cannot be more than one fourth and may be very much less.   This would indicate for the combined mass of the ejected masses a minimum value of the order of $10^{29}$ grams.

The permitted bright lines are formed in a different manner from the forbidden lines.   The discrete masses never predominate in their radiation, as is shown by the fact that their duplicity, though definite, is not conspicuous.   These conclusions are based upon unpublished microphoto-

metric measures of the Harvard plates, as well as on the published data of Lindblad and Öhman, McLaughlin, Merrill, and Bobrovnikoff. Most of the intensity of the permitted lines must be produced in the atmosphere of the nova, and the problem is to determine at what level the emission occurs. There seems to be no escape from the conclusion that the absorption lines are generally formed above the broad emission lines. This view seems first to have been reached by Belopolsky[18] for Nova Aurigae, although he was severely criticized for it by Vogel.[19] Belopolsky's conclusion is, however, fully substantiated by Sayer's investigation of the hydrogen absorption and emission in the spectrum of Nova Aquilae.[20] For Nova Herculis, Lindblad and Öhman,[17] describing the structure of the H and K lines, state: "The broad emission to the red side of the absorption probably corresponds to the deepest level, for simplicity we will call it Emission A. Its apparent displacement toward the red, compared with the normal position of the line, is probably entirely caused by the one-sided absorption in the higher levels, which cuts off the broad emission A on the side of short wave-lengths." Referring to the bright emission, which we should regard as coming from the approaching mass, they state: "The emission $H_2$ and $K_2$ . . . which must correspond to a very high level in the gaseous envelope, gets gradually *apparently* displaced toward the red." The same conclusion concerning the absorption overlying the emission lines has been drawn by the authors from the microphotometer tracings of the Harvard spectrograms of Nova Herculis.

The formation of absorption lines at high levels might be accounted for on the thin shell theory, except that there is no explanation for the persistence of the absorption for any length of time. The theory of continuous ejection, with its other advantages, provides an equally good interpretation without encountering this difficulty. We visualize the continuously ejected atmosphere as maintaining a density gradient proportional to the inverse square of the radius. As we have shown,[13] in all the upper layers of such an atmosphere there will be a great excess of ultra-violet radiation, as compared with the Planck energy distribution. This conclusion is based on the assumption of a mass absorption coefficient depending only on the temperature and electron pressure at any point. At increasingly higher levels in the atmosphere (composed mostly of hydrogen as we suppose that of the nova to be) the absorption coefficient beyond the limit of the Lyman series will increase rapidly as the temperature falls to a point where we might normally expect a small amount of neutral hydrogen to exist, if local thermodynamic equilibrium were even approximately maintained. Because of this high absorption, hydrogen will continue to be completely ionized in higher levels of the atmosphere, until we reach a point where the excess radiation beyond the limit of the Lyman series has been transformed into radiation of longer wave-length. Much of this

light will be concentrated into bright hydrogen lines, particularly Lyman $\alpha$; effectively a dilution process is taking place. But above this layer we should expect fairly normal atmospheric conditions to set in again, except for the excess of radiation in Lyman $\alpha$, and between Lyman $\alpha$ and the limit of the Lyman series. The excess radiation at Lyman $\alpha$ will keep the hydrogen atoms of the upper layers in a state to absorb the Balmer series, while the bright Balmer lines are emitted in the lower layers by the process just described.

The excess radiation between Lyman $\alpha$ and the limit of the Lyman series will maintain the emission lines of elements other than hydrogen, the excitation potentials of which are less than 13.54 volts. In the early post-maximum stages, radiations requiring higher excitation were not observed, and only began to exist toward the end of March, when the total brightness of the nova had begun to decrease, and the process of continuous ejection, as we have pictured it, to break down.

*Summary.*—The two components of Nova Herculis observed visually can be related to conspicuous features of the bright line spectrum, and appear to be two gaseous masses of low density, ejected from the central star, probably very early in the outburst.

The strong absorption lines seen in the early post-maximum stages are considered to be formed at higher levels than the corresponding broad bright lines, in a deep atmosphere built up by the continuous ejection of material from the surface of the original star. It is the latter process that produces the continuous background, while the doubled bright lines arise in the two ejected nebulous masses.

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