22. STARS OF T TAURI AND UV CETI TYPES AND THE PHENOMENON OF CONTINUOUS EMISSION

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Our knowledge concerning stars of the T Tauri and UV Ceti types has been considerably enlarged during recent years, owing to the accumulation of a large number of facts. As a result, we may now make certain suggestions regarding the causes of the non-stability of these stars, based on observational data. Such an approach to the solution of the problem is altogether different from that applied heretofore in attempts to develop a theory of certain types of variable stars. The method of construction of models has usually been applied in the past. We do not exclude, of course, the possibility of solving a problem on the basis of some theoretical model. However, the physical phenomena observed in the T Tauri and UV Ceti stars are so unusual that it is first of all necessary to define the nature of these phenomena and their mutual interrelation. Only then will detailed mathematical construction of a definite model be possible.

Let us, therefore, compare some facts relating to stars of the two above types, which seem essential to us when endeavouring to find out the nature of their variability.

T Tauri type stars are of interest since they are found in groups forming associations. These associations were named T-associations by us. It was found later on that this name was quite correct. It was discovered that between the T-associations and the usual O-associations there exists a definite connexion which manifests itself in the fact that some O-associations contain a considerable number of T Tauri variables and are, therefore, at the same time T-associations. A large number of T Tauri stars are contained, for instance, in the Orion association (shown by the studies of Parenago and Haro), and in the associations of Monoceros I and Perseus II, investigated from that point of view by Herbig.

The presence of T Tauri stars in the Perseus II association, which represents, according to Blaauw, a diverging group of hot stars, deserves particular attention. Since the youth of this group may be considered as established, it is natural to suggest that the T Tauri stars are also young objects.

We shall not discuss here some other arguments in favour of the youth of the T Tauri stars. Let us mention only briefly the most probable alternative suggestion; namely, that the T Tauri stars are ordinary dwarfs which have entered into a dust cloud at random. This was suggested by the fact that the T Tauri stars are actually met very often in dark or bright diffuse nebulae.

In Kholopov's study it was shown for the first time that the members of the T-association in Taurus are distributed in small, comparatively compact groups, and that the density of some of these groups is so large that it exceeds the partial density of dwarfs of corresponding luminosities in the surrounding stellar field. This fact contradicts the suggestion regarding ordinary dwarfs entering into the nebulae at random. Herbig has shown more recently that in the association of Monoceros 1 we observe still denser groups of T Tauri stars. Thus, the hypothesis concerning dwarfs that have accidentally entered a nebula must be rejected, and it should be accepted that the T Tauri stars forming a given group are of a common origin.

On the other hand, since the majority of T Tauri stars are found in diffuse nebulae, it should be considered that these stars lose their T Tauri properties previous to the dissipation of the nebula, or previous to their leaving the nebula. Since, according to modern ideas, the diffuse nebulae are unstable formations and must have ages of the order of 1–2 millions of years, we conclude that the T Tauri type stars cannot be older than 1–2 millions of years. The observed properties of the T Tauri stars must, therefore, be considered as connected with the internal properties of these young objects.

The representatives of the UV Ceti type known to us are located in the immediate neighbourhood of the Sun because, owing to their low luminosities, it is extremely difficult to observe such stars at greater distances. Therefore, the suggestion that there is a nebula associated with such stars is equivalent to the hypothesis that the Sun is located in a diffuse nebula. If we should admit this hypothesis, then we must assume that the density of that nebula is insignificant or at least so small that it exerts no influence upon the spectral features of the Sun. Any influence upon the faint M-type dwarfs which move rapidly across the nebula must be still less. Therefore, the appearance of bright lines in their spectra and, in particular, of outbursts arising under such influence, are out of the question.

Thus, in the case of the T Tauri type stars, as also in the case of the UV Ceti type stars, their variability and spectral properties are connected with the laws of internal evolution of such objects.

One of the most important features connecting the two classes of variable stars under discussion is the presence of continuous emission in the spectra of both types of stars. According to Joy, continuous emission is observed in UV Ceti during its outbursts, whereas in the T Tauri stars it appears at different stages of their light variation.

Over a year and a half ago, when we arrived for the first time at the conclusion that the causes of the continuous emission in the T Tauri and in the UV Ceti stars are similar, the results of Haro and his collaborators on the rapid variables in the Orion nebula and in other associations were not yet known to us. The discovery of rapid variables in T-associations by the Mexican astronomers appeared to link the UV Ceti and T Tauri stars, and showed that these two classes of variable stars, as well as the rapid variables, belong to the same large family of variable dwarfs. The most important property of this family as a whole is the appearance, from time to time, of continuous emission in their spectra. The physical interpretation of the processes going on in the atmospheres of these variables requires, therefore, an understanding of the causes and of the nature of the phenomenon of continuous emission.

Continuous emission manifests itself in various stars in quite different ways with respect to duration and intensity. Therefore, it becomes possible to exclude quite a number of hypotheses on the nature of the continuous emission and to approach, in this way, an understanding of the character of this phenomenon on the basis of known empirical data. The fact that extremely intense continuous emission is observed during outbursts of the UV Ceti type stars makes one assume that the increase of brightness is in these cases mainly caused by the continuous emission. Therefore, the problem of the cause of the increase in brightness is, at least sometimes, coincident with the problem of the continuous emission.

When the increase in brightness is caused by thermal radiation, it must be a consequence of either an increase in temperature, or an increase in the radius of a star.

Cases are known, however, when the increase in brightness occurs within a few seconds. Thus, during the outburst of UV Ceti on 24 October 1952, the brightness of the binary containing this variable increased more than 1·6 magnitudes within 7 sec. This means that the luminosity increased more than 4-fold. If the increase in brightness were to be explained by a change in area, it would signify that the radius of the star had become at least doubled in the course of 7 sec. This would require an expansion of the surface layer with a velocity of 50,000 km./sec. or more. This velocity is totally excluded since the simultaneously observed bright lines do not show any appreciable Doppler shift. It must be assumed, then, that the continuous emission is connected with a considerable increase in the temperature of the outer layers. The possibility that some increase may take place in the temperature of the stellar atmosphere as a result of the appearance of continuous emission cannot be denied. However, it is not this possibility that we are discussing here, but rather the possibility of the appearance of continuous emission itself as a consequence of an increase of temperature of the external layers.

Two possibilities require consideration in this connexion:

(1) The increase of temperature may be caused by an increase in the radiation flux, due to a change in the internal parts of the star. In this case an increase of temperature must take place not only in the photosphere, but also in the deeper parts. But then a decrease of the radiation flux might be possible only after these inner parts have cooled. This would require at least some hours because of the properties of the transport of radiation in the outer layers. However, the entire outburst of UV Ceti on 24 October 1952, including the descending branch of the light curve, took place in only 2 minutes. We must, therefore, reject the hypothesis regarding the heating of the atmosphere as a result of the increase of the radiation flux from the interior.

(2) The increase in the temperature of the external layers may occur as a consequence of the liberation of energy in the same layers. There are two possibilities in this case: (*a*) thermal emission in the external layers may result at the expense of the energy of some mechanical motion propagated from the internal to the outer parts, or (*b*) it results at the expense of some other sources of energy. If variant (*a*) is correct, we must expect something like a blast, embracing either the star as a whole or some of its regions. In this case, the phenomenon should always be of short duration; i.e. the transformation of the blast energy into thermal energy in the external layers and, consequently, the liberation of the continuous emission, should last an extremely short time. The phenomenon of continuous emission has, however, the following property: while in the case of outbursts of the UV Ceti stars the emission is observed for extremely short intervals of time, in some T Tauri stars, DD Tauri and BD $+67^{\circ}$ 922 in particular, it is observed to last over a period of years. Hence variant (*a*) must be rejected, and it must be supposed that continuous emission is liberated at the expense of some other supply of energy available in the atmosphere of the star. Since the total sum of thermal and other types of energy present at a given moment in those outer layers of the atmosphere where continuous emission originates is extremely small, we must admit that the sources of

energy of such emission are brought from the internal parts and only then are liberated in the external layers.

This possibility is apparently the only one which does not directly contradict observations. It is quite natural that if a rapid or slow liberation of some sources of energy (unknown to us at the present) is going on in the outermost layers of the atmosphere, then, owing to the transparency of these layers for continuous radiation, the liberated energy may be emitted without being transformed to any large extent into heat. It would exert, therefore, no major influence upon the mean kinetic energy of the particles in the corresponding layers of the atmosphere. The additional radiation liberated must therefore be of a quite different nature from thermal; i.e. it must be non-thermal radiation.

It must be asked what are the possible sources of energy that could be transferred from the internal to the external layers to give rise to continuous emission. Since we observe in some stars prolonged continuous emission, whose intensity is similar to that of the total thermal radiation of the star, it is natural to assume that the nature of such sources is similar to that of the internal sources of stellar energy: i.e. that these sources are connected with some nuclear processes. It is difficult to say anything definite concerning such nuclear processes at present. It is most probable that these processes of atomic decay are going on, however, not in microscopic atomic nuclei of the usual type, but in nuclear formations on a macroscopic scale, i.e. in such objects which are not yet known to us.

The picture of the changes going on in T Tauri stars is usually more complicated than in UV Ceti stars. Along with the phenomenon of continuous emission of variable intensity, there are also observed variations of colour temperature which cause changes in the thermal radiation. Besides, variations of the intensity of the emission lines are also superimposed upon the variations of the two other kinds.

To explain such a complex of phenomena it must be admitted, as was done in our paper published in the *Communications of the Burakan Observatory*, No. 13, that the liberation of the energy which comes from the internal parts of the star may take place in various layers of its outer envelope. If the energy is liberated below the photospheric layers, we shall observe an additional amount of thermal radiation passing through the photosphere, and comparatively slow light-variations. If the energy is liberated above the photospheric layers, we must observe an increase of the continuous emission and sharp light-variations. It is of interest that the intensity of the continuous emission of the T Tauri stars sometimes increases quickly, although the duration of the maximum may be of considerable length.

In the intermediate case, when energy is liberated in the photospheric layers themselves, we must expect to observe both an increase in the thermal radiation as well as in the continuous emission, together with superimposed absorption lines. In this case, obviously, it will be more difficult to distinguish the continuous emission from the thermal one. Let us finally point out that the bright line spectrum will also change, depending on the depth of the phenomenon.

I shall not discuss here in detail the relation of the phenomenon of continuous emission to the radiation of the comet-shaped nebulae. Data connected with it were communicated at the 1954 Liège Symposium. I should like only to emphasize that in some cases a considerable amount of the radiation of the comet-shaped nebula may be explained by a reflexion of the light of the variable star, but in other cases the reflected light of the variable plays almost no part, and the radiation of the nebula should be ascribed to continuous emission, originating from the direct liberation of energy in the nebula itself.

It seems to us that for a clearer understanding of the processes going on in T Tauri stars, it is extremely important to study those cases in which one aspect or the other of these processes is most pronounced. In other words, a more detailed study of some sub-types of variables of this class is very promising.

Let us discuss here in more detail four species of the above objects. We do not try to classify them, but choose these species only for the sake of emphasizing the necessity of a detailed study of such objects in which characteristic features of the phenomenon of continuous emission are shown most clearly.

First species. Here belong the T Tauri type objects with particularly prolonged and intense continuous emission. Owing to the peculiar distribution of the intensity of continuous emission with frequency, the ultraviolet regions of their spectra are extremely intense.

The most typical representatives of the above species are DD Tauri, studied by Struve and Swings, and LHα 61, discovered by Herbig in his investigation of the association in the neighbourhood of S Monocerotis.

It should be mentioned that the above stars have two more properties in common. The first is the presence of Balmer emission lines out to a high quantum number. The second property is their connexion with comet-shaped nebulae whose brightness greatly exceeds the maximum brightness which would be observed if the nebulae should only reflect the light of the stars.

As was shown by Haro, there are some blue objects among the variable stars of the Orion Nebula. The blue colour of these objects is doubtlessly caused by the distribution of energy in the spectrum of continuous emission. Haro found that in such cases the intensity of the bright Hα line usually is extremely high. Apparently these variables are, according to these properties, closely related to DD Tauri and LHα 61.

The comparatively small number of stars of this species and the particularly intense appearance in them of phenomena typical of the T Tauri stars, testify to the shortness of this stage of their evolution. It is, probably, the earliest stage of the existence of the T Tauri type stars.

Second species. These are the Herbig-Haro Objects. They consist of faint stars surrounded by gaseous nebulae of extremely small diameters. The spectra of these nebulae contain forbidden bright lines of a low degree of ionization. The absolute magnitude of the central stars of these Objects is about $+9^m$, about equal to that of DD Tauri. In spite of their low absolute magnitude, the nuclei of these objects are blue stars, according to Haro. It is natural to suggest in this case also, that the blue colour is not caused by high temperature but by continuous emission. It is of interest that in spite of the extreme rarity of these Objects, three of them located in the Orion association are distributed in the form of a short chain, 5 minutes of arc long. This cannot be a random coincidence and is evidence in favour of the extreme youth of these objects. It would be very desirable to find similar objects in other associations.

Third species. These are the rapid variables discovered by Haro and his collaborators in the Orion Nebula and in Taurus. The absolute magnitudes of these rapid variables are of the same order as the absolute magnitudes of other T Tauri stars, and differ from those of the UV Ceti stars. This species occupies, therefore, an intermediate position between the UV Ceti stars and the ordinary T Tauri stars, filling the intervening gap. It is interesting that the emission lines of these objects are not strong. In the spectra of other objects the continuous emission is accompanied by bright lines. It is, therefore, very important to establish whether in this case the increase of the brightness is connected with the increasing continuous emission, or whether it is caused by the increase of thermal radiation.

Objects belonging to this species, as well as the UV Ceti stars, show a rapid rate of liberation of energy. But it should not, however, be supposed that in other cases, when the phenomenon of continuous emission is prolonged, that the process of liberation of energy is also prolonged. It is not excluded that between the liberation of energy from its sources and its transformation into light quanta of the continuous spectrum there exists one more stage, the duration of which may be quite different in various cases.

Fourth species. This species has at present only one representative, but an extremely interesting one, namely the variable star BD + 67° 922 (=AG Draconis). Along with rather intense continuous emission, the following phenomena are typical for this star:

(1) The presence of extremely intense bright H lines and particularly of the bright line of λ 4686 of ionized helium.

(2) Its membership in the spherical component of our Galaxy, which is apparent both from its high galactic latitude (41°) and also from its radial velocity (about -140 km./sec.). The galactic longitude of this star is almost equal to that of the solar apex in respect to the stars of high velocity. The sign of the observed radial velocity is therefore explained. It is of interest that the radial velocity of BD + 67° 922 almost coincides with that of the high-velocity long-period variable R Draconis (the period of which is 245 days), located in its vicinity.

It is seen from this example that in the spherical component of our Galaxy there are also T Tauri type stars, the most important difference between + 67° 922 and the ordinary T Tauri stars met in associations being the presence of high-excitation He II lines.

As was mentioned above, the liberation of large amounts of energy in the outer parts of the T Tauri type stars and in the outermost layers of their atmospheres may be considered as the physical cause of the processes going on in these stars. It is likely that such liberation of energy is connected with nuclear processes. However, these processes are, according to their nature, altogether different from the already known processes of liberation of nuclear energy and particularly from the thermo-nuclear reactions. The fact that such liberation occurs in the form of explosions suggests a transfer of matter that is in a state of nuclear instability from the internal parts to the external layers. On the other hand, since these phenomena are observed in young stars it may be that the material which is being brought up from the interior contains pre-stellar matter of high density. It may represent matter that is in an altogether peculiar state, thus far unknown to us.

This point of view naturally meets the objection that the problem has here been ascribed to unknown physical processes, whereas not all the possibilities of explanation involving known physical laws have been exhausted.

It should, however, be stated that in studying a phenomenon, no matter how much it has been investigated, we can never be certain that all possible explanations of that phenomenon on the grounds of the existing laws of physics have been tried. Despite this, at some stage in the study, we have to consider that the phenomenon under investigation, which cannot be explained on the basis of known laws of theoretical physics, is a manifes-