FUORS

The characteristic trait of FU Orion type stars (fuors) is that they suddenly increase their luminosity in some spectral region by over a hundredfold within a short time span, and retain the enhanced luminosity for many years. An explanation is offered for this phenomenon, based on the assumption of presence, prior to the rise in the light–curve in the region adjacent to the star, of sources of corpuscular radiation. As indicated by observations, at the time of the rise in brightness, an envelope encompassing those external sources is developed. For that reason, following the rise in brightness, almost all energy from those sources is emitted in the form of thermal radiation flux.

If some rapidly unfolding phenomenon occurs, say, only once during the lifetime of a star, that phenomenon will be observed extremely infrequently among the stars surrounding us. However it may mark a regular and even major stage in the evolution of the stars or, say, of stars having masses within a certain specified range.

Here we wish to draw attention to a group of phenomena which is observed with extreme rarity and which may shed some light on the problems of stellar evolution.

1. FU Orionis Stars

At the close of the past year, we received from a Swedish astronomer Gunnar Wellin a preprint of his short report on a star Lk H_α 190 located in the North America nebula (NGC 7000) among a group of stars featuring bright lines (type T-Tauri, etc.) with the magnitude $m_{pg} = 16.0$ indicated by Herbig in 1957, and varying its brightness only slowly over the ensuing years, with $m_{pg} = 10.0$ reported in 1970 [1]. Comparison of various negatives indicates that an abrupt increase in brightness occured in late 1969. Since that time the brightness of the star varied slightly. According to photoelectric measurements taken by Grigoryan in mid-July 1970 (at Byurakan), its brightness was $m_V = 10.8$. We are dealing in this case with an abrupt rise in brightness similar to one witnessed in 1936 in FU Ori. Prior to the increase in brightness, the magnitude of the star FU Ori was 16, but it became brighter than a 10th magnitude star in 1936 following a flare; later on, after attenuating slowly, it eventually arrived at the magnitude $m_{pg} = 10.5$; since then the brightness has hardly varied at all. In both instances the star shifted abruptly from one state, in which its brightness fluctuated slightly about some low level to another state where it was approximately a hundredfold greater.

Because the higher level of brightness holds on for a period of decades at least we prefer not to use the term “flare stars” in this context. We will call these objects “fuors”.

Note that P Cyg furnishes essentially a similar phenomenon.

Prior to the brightness rise is this star was not visible to the unaided eye. Its magnitude is now $m_{pg} = 4.8$.

In the case of FU Ori, we know the approximate brightness prior to the rise in luminosity ($m = 16.0$). There is only one case (Lk H_α 190) where we know the spectrum prior to the rise in brightness: it corresponded to a T Tauri type late dwarf [2]. Unfortunately, owing to the small dispersion, Herbig was unable to give a determination of spectral type based on absorption lines. There are also other objects, in which an appreciable enhancement of brightness was observed within a short period of time, resulting in a more or less stationary state. We cannot exclude that these objects also belong to fuor–stars.

It is an essential point that both FU Ori, and especially Lk H_α 190, demonstrate, after the rise in brightness spectral features typical of stars of relatively high luminosity. In particular, in the star Lk H_α 190 the observed H_α emission line has an absorption component on the shortwave side which is displaced 420 km/sec. In other words, that star now features a continuous outflow of matter similar to that established in the case of P Cyg. Such an outflow of matter must result in an extended shell around the star. In addition, the atmospheres of Lk H_α 190 and FU Ori are rich in lithium, which is typical of young stars. Finally, the three stars belong to stellar associations.

Within usual concepts regarding stellar evolution, the shift of star from one level of more or less stationary luminosity to another level many times higher must be accounted for in terms of the total output of the energy sources present in the star. But it would be difficult to imagine that the internal structure of the star could vary to such an extent within a mere few months that the total output of the energy sources would increase more than a hundredfold. We therefore have to find some other explanation.

The gist of the explanation which we propose is that there exist intense and constantly active energy sources in the space above the photosphere in some or all of the T Tauri type stars, somewhere in the region of the corona or even higher. A portion of this energy is released in the form of nonthermal continuous emission in blue, violet and ultra–violet light. In some T Tauri type stars, this emission is so intense that it is observed directly in the form of an “ultra–violet excess” in the spectrum of the corresponding star (e. g. , XX Ori, NS Ori, NX Monocerotis). The maximum of this nonthermal emission is found in the far ultra–violet. However, it is not observable from the earth. In many cases, the “tail” of that excess extending out from the near ultra–violet observable from the earth, is so faint that it is not perceptible against the background of the star’s thermal emission in the same wavelengths. Nevertheless, the existence of the excess in the far ultra–violet can be ascertained with reasonable confidence from the existence of the emission lines in the spectra of those stars. We need not dwell here on which portion of the energy released by the nonthermal sources is converted to electromagnetic radiation and which portion is released in the form of the kinetic energy of corpuscular matter ejected into the surrounding space. However, if we assume that the energy released is the result of primary processes of nuclear decay type, then the conversion factor of that energy into photographic light observable from the earth's surface must be very small in those cases where the energy is released in the rarefied interstellar space. It is probably less than 0.01. All of the remaining energy in the supposed decay process must be released either in the form of the kinetic energy of the particles emitted or else in the form of short–wavelength electromagnetic radiation which is filtered out by our atmosphere.

On the other hand, if a shell which is opaque not only to shortwave radiation but also to high energy particles, developes around the star for any reasons whatever, then all of the energy due to sources located within the shell will be released in the form of thermal radiation of the shell. When shell temperatures are of the order of 10000° the convertion factor into photographic light will be close to unity.

In other words, the formation of an opaque shell must lead, under those conditions, to intensified conversion of the energy released by the presumed sources into photographic light, by a factor of more than a hundred.

Hence, we assume that we are not dealing here with an increase in the intensity of the sources of energy, but rather with an increase brought about by the development of the shell as the factor of conversion to photographic light of the energy released by the presumed sources.

The Concept of Calorimetric Stellar Magnitudes

The concept of visible and absolute bolometric magnitudes and bolometric corrections to the visual or photographic magnitudes have proved quite useful in discussions of stellar luminosity. In relation to bodies which emit corpuscular radiation appreciable compared with the amount of kinetic energy carried off, we introduce, a system of stellar magnitudes characterizing energy emitted in unit time, including both the total energy of the electromagnetic radiation and the kinetic energy of the corpuscles emitted. It is convenient to term this system the calorimetric system of stellar magnitudes. A natural definition of such stellar magnitudes is provided by the formula

$$m_{kal} = m_{bol} - 2.5 \lg \frac{L_k + L}{L}, \tag{1}$$

where L is the luminosity at electromagnetic wavelengths, and L_k is the total kinetic energy carried off in unit time by the particles emitted.

Let us now define the “calorimetric correction”

$$\delta' = m_{kal} - m'_{pg} \tag{2}$$

for a fuor prior to the rise in brightness. Subsequently, all stellar magnitudes referring to the stage preceding the rise in brightness, will be designated by a single prime, while those referring to the stage following the rise in brightness will be designated by double primes. The gist of our hypothesis can be expressed in terms of the equation

$$m_{kal} \approx m''_{bol}. \tag{3}$$

Upon comparing (3) and (2), we can state

$$\delta' \approx (m''_{bol} - m''_{pg}) + (m''_{pg} - m'_{pg}). \tag{4}$$

The first bracket in the right–hand term of (4) is the bolometric correction to the photographic magnitude after the flare. Since a fuor emits normal thermal radiation after the rise in brightness, this correction can be calculated on the basis of the effective temperature. For $T = 10000^\circ$, we have the value -0.4. The correction is probably good for both FU Ori and for Lk H_α 190. As for the second term in (4), it comprises the observed rise in brightness, which is 5 magnitudes in both instances. Hence, we have

$$\delta' = -5.4.$$

But the resulting calorimetric correction for a fuor which has yet to undergo a rise in brightness (hence, a prefuor) consists of two parts: the thermal emission (t) of the star and the nonthermal emission (nt) emanating from the source(s) located above the photosphere. Evidently, the factor of conversion of the energy released by those sources into radiation in the photographic portion of the spectrum is determined preponderantly by the second part. We therefore have to separately look for the calorimetric correction to the nonthermal radiation of a prefuor. We denote this correction as δ. We now have

$$\delta = m'^{nt}_{kal} - m'^{nt}_{pg}. \tag{5}$$

Let us now use the equation

$$10^{-0.4\, m'^{nt}_{kal}} = 10^{-0.4\, m_{kal}} - 10^{-0.4\, m'^{t}_{bol}},$$

where m_{bol} denotes the bolometric thermal radiation of the prefuor. The equation means that the calorimetric luminosity of the prefuor is on the whole the sum of the intensity of thermal radiation by the star and the calorimetric luminosity of the nonthermal sources (producing both corpuscular radiation and electromagnetic radiation). Taking (3) and (5) into account, we readily find

$$\delta = m'^{nt}_{kal} - m'^{nt}_{pg} = (m''_{bol} - m''_{pg}) + (m''_{pg} - m'^{nt}_{pg}) - 2.5\,\mathrm{lg}\left[1 - 10^{-0.4\,(m'^{t}_{bol} - m''_{bol})}\right]. \tag{6}$$

In essence, however, the last term is very small, so that we can resort to the formula

$$m'^{nt}_{kal} - m'^{nt}_{pg} \approx (m''_{bol} - m''_{pg}) + (m''_{pg} - m'^{nt}_{pg}). \tag{7}$$

Unfortunatly, we cannot determine the magnitude of the nonthermal component in photographic light from the spectral observations of the prefuor Lk H_α 190 by Herbig. But since this component is weak, we surmise that it accounts for not more than 15% in photographic light. That would mean $m\frac{nt}{pg} \approx 18.0$. On the other hand, the great intensity of the emission lines of the Balmer series in a prefuor spectrum argues in favor of a rather large excess in the far ultra–violet. That supports the assumption that the excess cannot be much less than the indicated 15% in the near ultra–violet. We can therefore settle for a rough assignment $m^{nt}_{pg} \approx 18.0$. Consequently, (7) yields, for Lk H_α 190:

$$\delta = m'^{nt}_{kal} - m^{nt}_{pg} \approx -7.4.$$

As we readily see from the tabulated bolometric corrections and color indices of Planck radiation, the highest value of the differences $m_{bol} - m_{pg}$ is attained at $T = 8000^\circ$ and is -0.2 [3]. Consequently, the value we obtained indicates that, in a prefuor, the factor for conversion of the energy into photographic light is at least 700 times less than in normal thermal radiation by F type stars, where it is at a maximum. All of that signifies that the rise in brightness experienced by a fuor is due to an at least several hundredfold, increase in the conversion factor.

3. Slow Flares and Fast Flares in Flare Stars

In the present section, it is our intension to go into somewhat further detail than was done in 1954 [8], on flares occurring in several late UV Cet type dwarfs in the vicinity of the sun, and in broader groups of dwarfs present in associations (Orion, NGC 2264, NGC 7023) and in young clusters (Pleiades).

The essence of the concept which we put forth at that time was that each flare is the result of liberation of some amount of energy which is heavily concentrated prior to the flare and is included in some portion of the "prestellar material". We deliberately eschewed constructing hypotheses on the nature of that prestellar material, only stressing the point that we were not referring to rarefield material, but rather to dense matter. Consequently, certain masses of that matter capable of existing in a stable state for a protracted period were in question, masses capable of being carried out into the space surrounding the star (possibly into the coronal layers, or even further, out to distances in excess of several stellar radii), and susceptible to almost instantaneous decay at those distances.

The fact that the phenomenon observed takes place above the star's photosphere, as a rule, follows from the particular energy distribution in the continuous spectrum of the flare (large ultra–violet excess). Here there are no significant quantities of absorbing matter, or conditions for thermalization of the emission spectrum. The fact that we are dealing here with an explosion, rather than a quiet expansion of the mass of hot gas ejected from the star, as proposed by several authors, is confirmed by photoelectric observations with a high time resolution, according to which the increase in brightness is often measured literally in second.

We have pointed out that in addition to the cases where the energy is released above the photosphere layers we can conceive of cases where the energy is liberated underneath the photosphere layers. The latter cases can be separated in turn into two groups:

1) Release of energy occurring deep down in the inner layers of the star, with the energy working its way up to the surface over the course of many months or years. In that case, the very process of energy release will become, extended at least by a matter of weeks or months. That means that we shall not be observing any separate and distinct flares, but only their overall averaged result, which reduces to some small increase in the brightness of the star.

2) The release of energy takes place directly beneath the photosphere layers, at a depth from which the enrgy makes its way (via diffusion of the radiation or an ionization wave) to the surface in the course of several hours. The observed flare process must last several hours in that region. The process of the rise in brightness of the star must proceed at a much slower pace than in those cases where the liberated energy advances above the star's surface, and the color of the additional radiation must be a function of the amplitude of the brightness. The lower that amplitude, the lower must be the color temperature of the additional radiation.

Professor Haro, in his first observations of "slow flares", which differ radically in their nature from "fast flares", fully confirmed the existence of two classes of flares in flare stars in the constellation Orion, and the recent discovery by Parsamyan [7] of a slow flare in the Pleiades showed that slow flares are also uncountered in members of older aggregates than the Orion association.

We would now like to focus attention on some quantitative data derived from observations which proved to be in close agreement with our hypothesis on the nature of fast and slow flares.

The problem is that, if the flares are the result of disintegration of dense matter, i.e., of some mass of nuclear density, into an assemblage of particles, then conversion of the decay energy into the optical radiation at the frequencies we observed will be very small in the vacuum. Most of the decay energy will become converted either into the kinetic energy of the particles formed (as occurs, for example, in β decay) or into electromagnetic radiation such as γ photons, x–ray photons, or radiation in the far ultra–violet.

An entirely different state of affairs prevails when decay takes place underneath the photosphere layers. In that case, all of the decay energy, except perhaps for neutrino energy, will become converted into the thermal energy of the star's radiation. In other words, the total flare energy in the form of optical light must be many times greater in those cases than in the case of fast flares. This relationship is difficult to define, as it comprises only a concrete mechanism acting in the flare process. One of the possible concretizations to consider is the mechanism proposed by Gurzadyan, wherein anti–Compton scattering of quanta of the star's thermal radiation takes place on the electrons (or positrons) released in the decay process. When that mechanism is at work, the conversion factor must be below 0.01. Then the energy at optical wavelengths must be a hundred times greater, in slow flares, than the enrgy at optical wavelengths released in fast flares.

Observations show that: 1) slow flares are observed many times less frequently than fast flares; 2) the amplitudes observed in slow flares are not smaller than those observed in fast flares; while the largest amplitudes of fast flares in photographic light attain a mgnitude of 5 in the Orion stellar association, one of the slow flares observed in Orion (at the star VZO 177) by Haro had an amplitude of 8.4 in that range of light; 3) the color of the emission of slow flares is redder than that of fast flares.

The first of the circumstances enumerated here seems to be due the fact that the energy must be released in a layer of relatively small linear thickness (possibly of the order of a hundred kilometers) beneath the photosphere (case 2) in order for a slow flare of some appreciable amplitude to be observed. For instance, if we assume that the decay of masses ejected outwards takes place more or less spontaneously, then the decay probability in any layer must be proportional to the residence time in that layer, i.e., must be proportional to the thickness of that layer. In that light, the infrequency of slow flares presents no difficulty to understanding.

The second of these circumstances is a direct indication that the observed total energy of the optical radiation emitted in slow flares is several tens of times greater than the total energy observed in the optical range in fast flares, since the duration of the slow flare is tens of times longer when the radiation intensity is of that order of magnitude. Consequently, the observed relationship slow and fast optical flares is in complete accord with the concept of different values of the conversion factor on those two instances which we developed above.

In sum, the available data on differences between slow flares and fast flares confirm the hypothesis to the effect that flares are associated with high–energy decay processes.

4. Duration of the Postfuor Stage

In sum, we can safely infer from the available data on fuors that the process by which the brightness rise takes place is associated with the following transition:

T − Tauri type stars		*Fuor phenomenon*		*A type stars with*
with UV excess	⟶	brightness rise	⟶	P Cygni characteristic
(prefuor)		(shell formation)		(postfuor)

Even though postfuors probably represent a group of objects which is fairly homogeneous in many physical properties, it should still be pointed out that the absolute magnitudes are close to zero in the two cases in question (FU Ori and Lk H 190), whereas the absolute photographic magnitudes are of the order of -7.0 in P Cygni itself, and also in other P Cygni type objects found in O–type associations. It should be acknowledged that we are not yet in a position to state from which objects P Cyg type supergiants originate, but their frequent presence in O–associations suggests that here too the initial phase was a T– Tauri type star with energy sources of enormous intensity.

Once the frequency of occurrence of fuors is known, as well as the number of objects with a P Cyg spectral characteristic, we would be able to estimate roughly the duration of the postfuor stage, or more precisely that portion of it within which a continuous outflow of matter continues to occur.

Only two typical fuors have been observed in the last 50 years (i.e., since 1920), and these were stars brighter than $11^m.0$ after their brightness had stabilized. Of course, there may have been cases where the fuor phenomenon escaped notice. But it must be assumed that if two plates taken at protracted times apart (on the order of a score of years or more) were ever compared for a given region of the sky, fuor becoming brighter than $11^m.0$ and flaring over the time period elapsed between the two plates taken in that portion of the sky would have to be detected with a probability close to unity. Even though such comparisons have been carried out so frequently at observatories given region of the sky, fuor becoming brighter than $11^m.0$ and flaring over the time period elapsed between the two plates taken in that portion of the sky would have to be detected with a probability close to unity. Even though such comparisons have been carried out so frequently at observatories that they undoubtedly encompass most of the northern hemisphere, the time intervals between two plates are still not very long. Even if we assume that the value of the maximum time interval Δt, averaged over the entire sky, for which the comparison was carried out, was 20 years (assuming $\Delta t = 0$ with the averaging, if no such comparisons were carried out all), it would be found that we could detect only 40fuorized stars becoming brighter than $11^m.0$ in the last 50 years, in the best case. Then the total number of stars fuorized during this half–century in the northern hemisphere will be of the order of 5; in other words, a single star fuorized in one decade on the average. On the other hand, if T is the average duration expressed in years that postfuor phase when the P Cygni characteristic in the spectrum is still detectable and, moreover, the brightness shows no appreciable decrease, then we must have

$$N_p = 0.1 \cdot T$$

for the total number N_p of stars brighter than 11.0 with a P–characteristic. Unfortunately, the available data are not sufficient to estimate the N_p number. However, not more than 10 or so stars with a P–characteristic are known [5] among the stars in the HD catalog of the northern sky. Herbig [6] has made a detailed investigation of the spectra of stars associated with cometary nebulae, but could detect only 4 stars with a P– characteristic, and one of those was, however, of magnitude $13^m.0$. Nevertheless, it can be safely assumed that a more detailed study of the spectra of most of the HD stars, particularly in the region of the H_α line, will result in doubling or even tripling the number of objects discerned with a P–characteristic. In addition, the HD catalog contains only a small portion (about a third) of the stars brighter than $11^m.0$. Consequently, a crude assumption would be $N_p \approx 60$ in the northern sky. That would mean that the duration of the postfuor stage we are interested here must be of the order of 600 years. By the way, we have to be careful in reaching our conclusions, since we do not know the true frequency of occurrence of fuors becoming transformed into P Cyg type supergiants, not even roughly. The lifetime of these supergiants can be much greater than in postfuors of lower luminosity.

There is no doubt, however, that the phase of the P Cyg type spectrum in postfuors of low luminosity is not very protracted. Our calculations were very rough, but we can still state with some assurance that the postfuor stage will not last longer than a time on the order of a thousand years, in those instances. But we then are confronted with the question of what happens after that stage has gone to completion; i.e., we have to deal with what we might call the postpostfuors, and whether the star resumes its initial brightness, i.e., reverts to the brightness of a prefuor or, on the contrary, retains its enhanced brightness. It would be difficult to venture an answer to that question at the present time. The only point that is certain is cases of an abrupt fall–off in brightness (the antifuor case) have not yet been discovered to date. We are then left with two probabilities: retention of the level of brightness achieved, or a gradual elimination of the shell with a fall–off in brightness for decades or centuries. But if the first possibility held, then as many as tens of millions of postfuors exhibiting visible brightness greater than the 11th magnitude would have had become accumulated over the course of, say, hundreds of millions of years. But there is in reality no such quantity of stars brighter than 11th magnitude. We therefore have to conclude that the brightness of the star must decline again within a short time.

Other assumptions are also warranted. At the present stage, we prefer hold back from a detailed discussion of those options.

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REFERENCES

1. G. H. Herbig, IBVS, no. 543, 1971.
2. G. H. H. Herbig, Ap. J., 128, 259, 1958.
3. C. W. Allen, Astrophysical Quantities, Athlone Press, London, 1955.
4. G. Haro and É. Parsamyan, Bol. Obs. Tonatzintla, 5, no. 31, 45, 1969.
5. P. Merrill and C. Borwell, Ap. J., 78, 87, 1933.
6. G. H. Herbig, Cotr. Lick. Obs., Ser. II, no. 99, 1960.
7. É. Parsamyan, Astrofizika, 7, 500, 1971.
8. V. A. Ambartzumian, Soobshch. Byurakan. Obs., no. 13, 1954.

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