3. THE ROLE OF ACCRETION IN STELLAR EVOLUTION

By F. Hoyle

The development of astronomical knowledge has now reached a stage where a precise description of the details of star formation has become a major issue. The enormous degree of contraction that occurs in stellar condensation, a concentration sufficient to increase the density of material from, say, 10^{-22} gr./cm.^{3} up to ultimate values of the order of 1 gm./cm.^{3}, gives a sure indication of the important part played by gravitational forces. Apart from gravitation, gas pressure must be accorded a significant place in the early stages of the process. It has been suggested that radiation pressure should also be included among the forces that determine the onset of condensation.

The present contribution is not, however, concerned with the problem in its most general aspects, but with the contribution of gravitation alone. When a star or a stellar condensation manages to capture additional interstellar gas through the action of gravitational force, without hydrodynamic connexion between star and gas being essential, we speak of accretion of interstellar gas. The problem of accretion of interstellar gas can conveniently be divided into two parts: one part in which any mass motion that the star possesses relative to the gas is less than the velocity of sound in the gas; and the other part in which, contrarily, the star possesses a mass motion exceeding the velocity of sound. In this connexion it should be remembered that stars probably condense only when the temperature of the gas is small; hence the relevant sound velocities are small—of the order of 1 km./sec.

The principle of accretion is very simple. Gravitation tends to produce compression in the gas. Gravitational potential energy is thus converted partly into heat, and partly into a mass motion of the gas. Heat is then radiated so that the total energy of the gas is reduced. Hence even if the gas has initially a positive total energy loss may be sufficient to prevent ultimate escape from the star. Whether this process is indeed strong enough to lead to material being captured by the star depends on its distance from the star. At very great distance the effect is too weak, while at sufficiently small distance the effect is strong enough to promote capture. Accordingly we can think of a critical distance above which capture occurs. The value of this critical distance has been calculated for a number of cases, the answers turn out to be always of the order GM/V^2 where G is a gravitational constant, M the mass of the star or stellar condensation, and V the velocity important in the problem—in the first case referred to above V represents the velocity of sound in the gas, in the second case it represents the velocity of mass motion between gas and star. This general result leads to a rate of accretion that can be written in the form

$$AG^2M^2\rho/V^3,$$

where ρ is the gas density, and A is a numerical coefficient of order 4π that depends on the precise details of the problem under discussion.

Application of this formula shows that accretion is only a major astronomical process, it only promotes significant star growth when V is not much greater than 1 km./sec. Now there is always a period during the early history of stars when V is of this order. Indeed it seems that the very birth of a star is intimately associated with this process. We may think of the formation of an initial condensation by some random process as the first stage in the birth of a star, and of the accretion process as being the second stage. The interesting query is: what fraction of the present mass of a star was contributed by the first stage and what by the second? A reason will be given later for the view that the mass of the star in the first stage is small compared with the mass attained by accretion.

Now general perturbations affecting an assembly of stars and gas tend to affect the stars differently from the gas, and hence gradually lead to appreciable relative velocities developed between stars and gas. Initially the relative velocity must be less than 1 km./sec. Finally, the velocity becomes of order 15 km./sec., or perhaps even more in some cases. Thus we see that perturbations must lead to accretion being eventually cut down to comparatively small proportions. Every star has therefore one temporary initial period of rapid accretion. We shall now see that a small fraction of stars may have a second or even a third period of rapid accretion.

To consider this point, we notice now that the interstellar gas is mainly condensed into clouds. The stars are formed inside these clouds. Perturbations lead to a relative velocity developing between a star and the particular cloud in which it happened to condense, thereby causing the star to move out of its parent cloud. In such a way, the stars come to move in a space that is irregularly dotted with clouds of gas.

Consider next a group of stars with the same mean motion in the Galaxy as an assembly of clouds, but with both individual stars and clouds possessing peculiar velocities in addition to their common mean motion. Then the chance can readily be estimated that a star, chosen at random, will encounter a cloud at relative speed less than 1 km./sec. Thus if U is a measure of the scatter of peculiar velocities among both the stars and the clouds the chance of such an encounter occurring at a speed less than $V (V \ll U)$ is given roughly by $(V/\sqrt{3}U)^3$—the number 3 in this formula arising from the fact that there are three independent components of velocity. For $V=1$ km./sec. and $U=15$ km./sec. the chance is about one in ten thousand. Now since a star may encounter as many as one hundred different clouds during its whole lifetime, we therefore see that the chance that a particular star during its lifetime encounters a cloud, other than its parent cloud, at relative speed less than 1 km./sec. is about one in a hundred; the chance that two such clouds are encountered is about one in a million.

Thus about one star in a hundred will experience a second period of rapid growth by accretion and one star in a million will experience both a second and a third such period.

At this stage we may seek confirmation of these considerations. Perhaps the example that best combines both interest and importance is the origin of binary systems. It is well known that binaries are of widespread occurrence and that the separation of the components in binaries may vary from many astronomical units down to values which are so small that the two components are effectively in contact with each other. Thus the separation can vary from one binary to another by a factor of as much as 10^4. Not only this, but observational evidence is suggestive of a continuous range of separation; that is to say, all values for the separation over the whole ten thousandfold range seem to occur. This circumstance would seem to point to a common origin for all binaries.

Now the present theory can be related to binary origin by the following considerations. Suppose that a set of stars forms concurrently as a group—there is independent evidence that stars tend to form in groups. During the early stages of the process widely separated binaries are frequently formed by stellar encounters—that this happens is well known and has been generally agreed.

What has not been previously understood is how very wide initial separations can be changed into much smaller separations, as is necessary to explain the origin of the close binaries. Accretion provides a process capable of achieving such a dynamical evolution. Thus it can be shown that as accretion proceeds the principle of the conservation of angular momentum requires that the separation of the components shall decrease approximately as the inverse cube of their masses. Hence binaries that are formed before the main increase of mass occurs will evolve with rapidly decreasing separation. Here then we have the reason why it seems probable that accretion plays an important role in increasing the mass during star formation. Now to give an example, a binary that first forms when the components are both of mass $\odot/3$, and in which the initial separation is 10^{15} cm., can evolve into a binary with both components of mass $\odot$ and separation about 4×10^{13} cm., or into a binary with both components of mass $3\odot$ and separation 10^{12} cm.

It is particularly to be noted that if we suppose that stars become totally condensed before wide binaries are formed the evolution process just discussed is completely lost. The essential features are:

(i) formation of condensations within a gas cloud,
(ii) condensations tend to form wide binaries;
(iii) subsequent growth by accretion produces both a growth of the components and a marked reduction in their separation.

The present discussion it may be noted does not preclude the formation of very close binaries, such as the W Ursa Majoris stars, by an independent process.

In conclusion it must be stressed that these considerations only outline the nature of the accretion process. Many other features concerning star condensation are of great importance. The relation of star formation to rotation, for example. Or again, a general discussion of the rate of condensation of interstellar gas into stars raises interesting questions. Why do stellar condensations apparently form at such a rate that the total mass of the gas in the spiral arms of our galaxy is comparable with the total mass of the stars?

This circumstance is scarcely an accident, applicable only to a particular neighbourhood in the Galaxy, since it is a condition that seems to occur in all galaxies with type I populations. Or again: why is the solar mass typical of stellar mass in general? Why are $\odot/1000$, or $10\,\odot$ not typical masses?

Discussion sur l'exposé de HOYLE

Schatzman rappelle le schéma de l'accrétion donné par Bondi et Hoyle en 1944,[*] dans lequel le rayonnement des molécules d'hydrogène excitées par choc joue un rôle important. Il fait remarquer que la valeur de la force d'oscillateur de la molécule d'hydrogène est un million de fois plus grande d'après Spitzer[†] que celle supposée par Hoyle et Lyttleton en 1940.[‡] Il peux que ce changement modifie le schéma de l'accrétion.

Hoyle ne pense pas que ce facteur 10^6 modifie le schéma de l'accrétion. Il est important que la température du milieu interstellaire ne s'élève pas au cours de l'accrétion. Hoyle ne pense pas que cette nouvelle valeur numérique modifie beaucoup le résultat du calcul de la température.

A. G. Masevich demande comment on explique en théorie de l'accrétion que les étoiles les plus massives aient aussi le plus grand moment angulaire.

Hoyle montre que le rayon de capture croissant avec la masse, les irrégularités du milieu interstellaire suffisent à expliquer le grand moment angulaire des géantes bleues.

Masevich demande comment on explique en théorie de l'accrétion la formation de binaires comportant une étoile O et une naine de la série principale.

Hoyle estime que loin de s'atténuer, la différence entre les deux composantes d'une étoile binaire s'accentue au cours de l'accrétion.

Kopal demande si la vitesse des binaires serrées n'est pas trop grande pour que se produise le phénomène d'accrétion.

Hoyle dit que la vitesse d'accrétion ne dépend que de la vitesse du centre de gravité par rapport à la matière interstellaire. On calcule ainsi la masse de matière capturée par l'ensemble des deux étoiles. La capture par chacune des deux étoiles est un problème différent et le calcul est très difficile.

Kopal demande comment Hoyle explique les binaires dont les deux composantes sont très différentes.

Hoyle: Le partage de la masse au cours de l'accrétion se fait sans doute proportionnellement au carré de la masse ou encore proportionellement à la surface de collision.

Kopal attire l'attention de Hoyle sur une étoile comme ζ Aur où le rapport des masses est environ 3 et le rapport des rayons environ 100 et demande l'origine de la différence.

Le Président suggère que la discussion continue dans le privé et donne la parole à M. Severny.

[*] *M.N.* **104**, 273–82, 1944.

[†] *Ap. J.* **109**, 337, 1949.

[‡] *Proc. Camb. Phil. Soc.* **36**, 424, 1940.

He pointed out that the existence of magnetic fields of 10^{-6} gauss in galactic space seemed to be very probable. 'Now [he continued], if you consider the growth of condensations out of diffuse matter in the presence of a magnetic field, you will obtain a picture essentially different from what is described by Dr Hoyle. Instead of condensations of spherical form you can obtain, as our calculations show, filaments, stretched along the lines of force of the magnetic field. It is due to the anisotropy of the conductivity of ionized matter in a magnetic field. We have considered the problem of gravitational instability of a nebula in the presence of a magnetic field and our calculations showed that the stability depends on the angle between the direction of motion and the direction of the magnetic field, i.e. the gravitational instability is an asymmetric phenomenon in the presence of a magnetic field. This shows that the process of formations of condensations in this case is different from what is considered by Dr Hoyle. It should be emphasized that the influence of magnetic fields in the Galaxy cannot be ignored in cosmogonical considerations.'

Hoyle dit qu'on ne doit pas supposer la présence d'un tel champ magnétique que la contraction ne puisse se produire, car les étoiles ont été formées.

Ambartsumian envisage les possibilités suivantes:

1° Il y a une grande dispersion dans les vitesses turbulentes dans une nébuleuse gazeuse et alors l'accrétion est impossible.

2° Il n'y a pas de dispersion des vitesses (les vitesses sont inférieures à 1 km./sec.). Mais il faut tenir compte du rôle de la raie $L\alpha$. La pression de radiation due au rayonnement en $L\alpha$ provenant des étoiles massives est si grande que la matière est littéralement soufflée.

3° Supposant que l'accrétion se produise peu à peu, au cours de rencontres au hasard d'un grand nombre de nuages, on ne comprend pas pourquoi il y a des associations O.

Si les étoiles de grande masse se produisent par l'accrétion à travers trois nuages successivement, on doit se demander pourquoi elles sont groupées au même endroit.

Hoyle est d'accord sur le premier point. Si la turbulence ou la température sont trop élevées, il n'y a pas d'accrétion. La température ou la turbulence doivent être basses.

En ce qui concerne le deuxième point, Hoyle affirme avoir pris une densité assez élevée pour que le phénomène décrit par Ambartsumian ne soit pas à craindre. Ce dernier conteste que ce soit possible.

En ce qui concerne le troisième point, Hoyle fait remarquer que l'accrétion ne se produit que lorsque la vitesse relative d'une étoile et d'un nuage est faible. En raison de la dispersion des vitesses spatiales des nuages et des étoiles, l'accrétion ne peut se produire que pour des étoiles dont la vitesse spatiale est comprise entre d'étroites limites, ce qui explique la formation d'étoiles O et B en groups d'étoiles de même vitesse.

4. QUELQUES RESULTATS DES RECHERCHES SUR LES NEBULEUSES GAZEUSES DIFFUSES ET LEURS RAPPORTS AVEC LA COSMOGONIE

Par G. A. Shajn (*membre de l'Académie des Sciences de l'U.R.S.S.*) et V Th. Gase

La matière gazeuse diffuse se manifeste dans l'Univers sous les aspects les plus divers et ses rapports avec les autres formes de la matière, avec les étoiles et la poussière interstellaire, sont fort complexes. Bien peu de données sont connues dans ce domaine pour qu'on puisse se faire une conception du rôle de la matière diffuse dans la cosmogonie. Nous nous permettrons de nous limiter à un exposé de quelques faits ayant probablement rapport à la cosmogonie, faits que nous avons recueillis au cours des 2–3 dernières années à l'observatoire de Siméiz.

A l'aide de chambres photographiques à grande ouverture de 640 et 450 mm. (f 1·4) nous avons photographié dans les rayons $H\alpha$ la presque totalité de la ceinture galactique dans les limites $\pm 10°$ Les documents contenant plus de 300 nébuleuses gazeuses dont 2/3 environ n'avaient pas été notés auparavant ont servi de base à notre étude.