INTERSTELLAR CLOUDS AND THE FORMATION
OF STARS

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Abstract. Part I gives a survey of the drastic revision of cosmic plasma physics which is precipitated by the exploration of the magnetosphere through *in situ* measurements. The 'pseudo-plasma formalism', which until now has almost completely dominated theoretical astrophysics, must be replaced by an experimentally based approach involving the introduction of a number of neglected plasma phenomena, such as electric double layers, critical velocity, and pinch effect. The general belief that star light is the main ionizer is shown to be doubtful; hydromagnetic conversion of gravitational and kinetic energy may often be much more important.

In Part II the revised plasma physics is applied to dark clouds and star formation. Magnetic fields do not necessarily counteract the contraction of a cloud; they may just as well 'pinch' the cloud. Magnetic compression may be the main mechanism for forming interstellar clouds and keeping them together.

Part III treats the formation of stars in a dusty cosmic plasma cloud. Star formation is due to an instability, but it is very unlikely that it has anything to do with the Jeans instability. A reasonable mechanism is that the sedimentation of 'dust' (including solid bodies of different size) is triggering off a gravitationally assisted accretion. A 'stellesimal' accretion analogous to the planetesimal accretion leads to the formation of a star surrounded by a very low density hollow in the cloud. Matter falling in from the cloud towards the star is the raw material for the formation of planets and satellites.

The study of the evolution of a dark cloud leads to a scenario of planet formation which is reconcilable with the results obtained from studies based on solar system data. This means that the new approach to cosmical plasma physics discussed in Part I logically leads to a consistent picture of the evolution of dark clouds and the formation of solar systems.

PART I
THE NEW APPROACH TO COSMICAL PLASMA PHYSICS

I.1. Introduction

The problem of how stars are formed has always been a key question in astrophysics. There seems to be a general agreement that stars are formed out of interstellar clouds, but there is no consensus through which process or processes this occurs. In fact there are dozens of theories and hundreds of papers presenting different opinions (for a general survey of the literature see, e.g., von Hoerner, 1968; Larson, 1973; Strom *et al.*, 1975).

There are convincing arguments for the view that the clouds out of which stars condense are ionized. The problem of star formation therefore naturally belongs to the field of cosmic plasma physics. This domain of science is at the present time

subject to a drastic revision (see, for example, Alfvén, 1968, 1977a; Block, 1976; Fälthammar, 1977). In order to have any hope of understanding how stars are formed this new approach to plasma physics must necessarily be taken into account. An introductory description of this subject is given in the remainder of Part I.

Where the condensation of interstellar clouds has previously been treated in the literature, magnetic fields have generally been considered to obstruct the process. This point of view, however, is not unconditionally true. On the contrary, magnetic fields will, under certain conditions, promote the contraction of interstellar clouds or may even constitute the main mechanism for contraction. This matter is further discussed in Part II. Finally, in Part III, a description is given of how stars may be formed out of a dusty plasma cloud by means of processes similar to those that once gave rise to the planets and satellites around the Sun.

I.2. The Theory of Cosmic Plasmas

The development of theoretical plasma physics started as a generalization of the kinetic theory of gases, by introducing the properties of charged particles. This formalism had almost no contact with experimental plasma physics, which during half a century of research had demonstrated that a plasma exhibited a large number of phenomena which were difficult to explain theoretically. The first serious confrontation of theoretical plasma physics with experiments led to what has been called the thermonuclear crisis, which showed that fusion reactors could not be constructed with guidance from the early theories. In reality this demonstrated that the theories were basically wrong. Later, *in situ* measurements of the magnetospheric and interplanetary plasmas led to a similar confrontation with the same disastrous result for the early theories. The result of this has been a new approach ('the second approach') to plasma physics which implies a replacement of the old 'pseudo-plasma' theories by new theories founded on plasma experiments (Alfvén, 1968, 1975a; Block, 1976).

The most important task in present cosmic plasma physics is to transfer the new approach from the laboratory and magnetosphere to astrophysics in general. We can expect that this will lead to a drastic revision of cosmic plasma physics in general, including the physics of interstellar clouds and the formation of stars in them.

I.2.1. PLASMA AND PSEUDO-PLASMA THEORY

The new approach should be based on the properties of plasmas which have been found by laboratory research, especially during the last 20 years. Thermonuclear research has given a major contribution to this, resulting in basically new views on the nature of a plasma. Many of the new results are applicable to cosmic plasmas. Still more important for cosmic applications of plasma physics are a long series of plasma experiments which have been made with the specific purpose of clarifying cosmic phenomena (for a review see Fälthammar, 1974; Block, 1976). The experiments
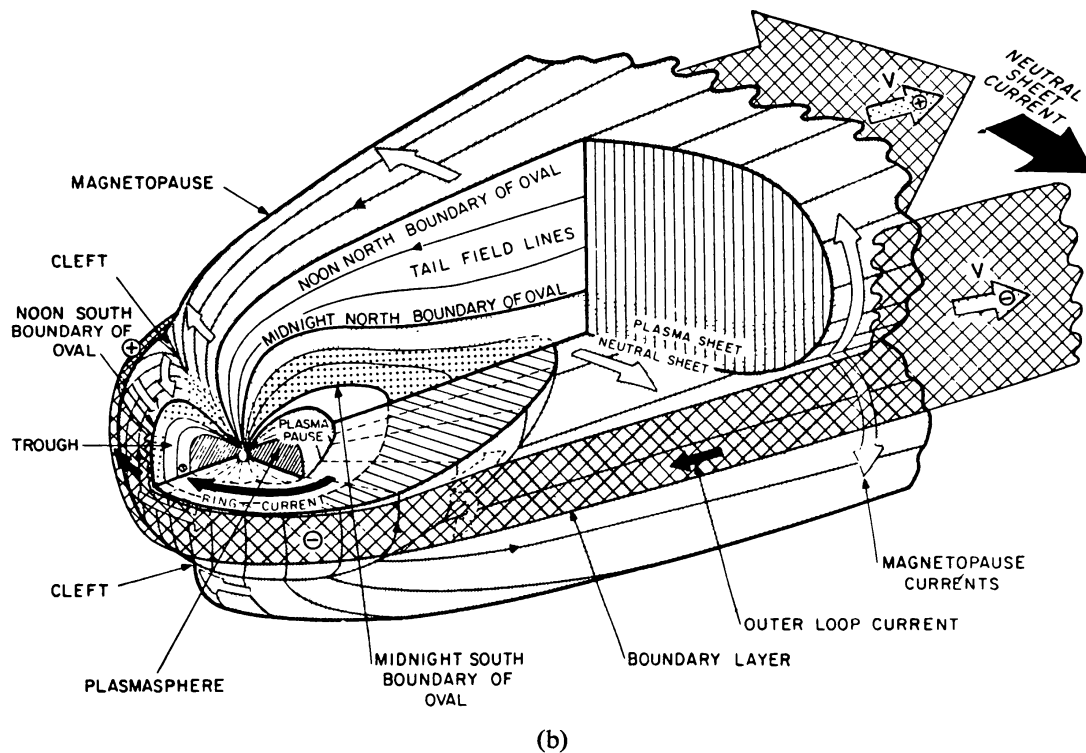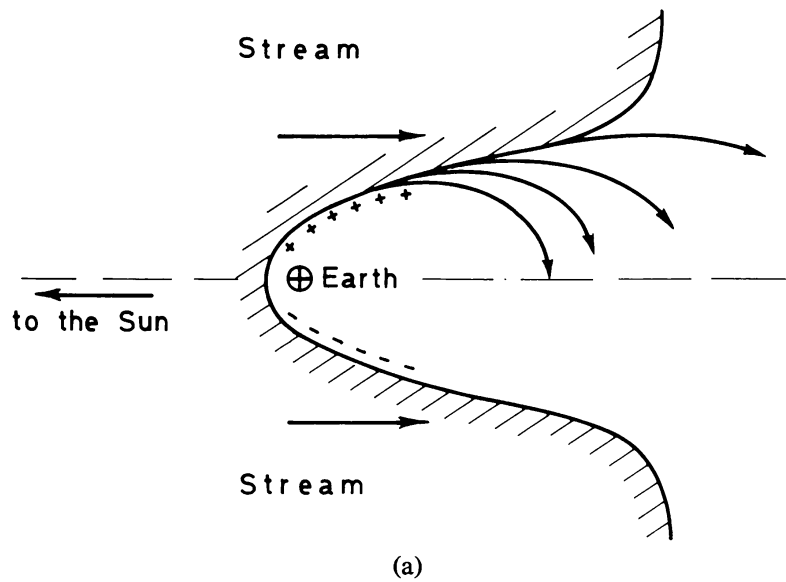
(a)

(b)

Fig. 1.   Magnetospheric model before (a) and after (b) impact of measurements in the magneto-sphere. (Figure 1(a), drawn after Chapman and Bartels, 1940; Figure 1(b), copy from Heikkila, 1972.) Astrophysics in general is now ripe for an equally drastic revision.

have been combined with a thorough theoretical study of the difficult problem of how to scale phenomena from the laboratory to astrophysics, including the elimination of wall effects.

The transfer of knowledge from the laboratory has led to a new treatment of magnetospheric phenomena. The conclusions from laboratory research are now combined with the wealth of *in situ* measurements in space. In this way a new cosmic plasma physics is built up. How drastic the change is can be illustrated by a comparison of Figure 1(a) (Chapman and Bartels, 1940), which represents the old 'pseudo-plasma' approach before the beginning of the space age, and Figure 1(b) (Heikkila, 1972), which shows a modern model of the magnetosphere.

Astrophysics in general is now ripe for an equally drastic revision.

I.3. General Properties of Cosmic Plasmas

Some general remarks: For the description of cosmic plasmas, homogeneous models are obsolete. As far as we know, most cosmic low density plasmas have a filamentary structure, produced by electric currents. There are often stable current layers in which the magnetic field may change 180° within a few Larmor radii.

I.3.1. DOUBLE LAYERS AND FROZEN-IN FIELD

Especially when currents flow parallel to the magnetic field, the plasma has a tendency to set up electrostatic double layers in which the electrostatic potential changes significantly within some tens of Debye lengths (Langmuir and Mott-Smith Jr, 1924; Alfvén, 1958; Carlqvist, 1969, 1972; Block, 1972, 1975, 1977; Torvén and Babić, 1976). This means that the 'frozen-in' magnetic field concept is invalid.

I.3.2. ENERGY TRANSFER

Furthermore, an 'invisible' energy transfer $dW/dt = I \cdot \Delta V$ (Alfvén, 1977a) can take place by means of an electric current I dissipating energy in a double layer with voltage drop ΔV. From a source of energy, e.g. the kinetic energy of a moving plasma, energy can be transferred to a distant region where it is released in particle acceleration or noise generation. It should be observed that *the current I may very well consist exclusively of low-energy particles*. This mechanism should not be confused with the energy transfer by means of high-energy particles accelerated in one region and releasing their energy in another and possibly distant region.

I.3.3. CRITICAL VELOCITY

When a magnetized plasma moves in relation to a non-ionized gas with a velocity exceeding the 'critical velocity'

$$v_{\mathrm{crit}} = \left(\frac{2eV_{\mathrm{ion}}}{m_a}\right)^{1/2},$$

(I 1)

where V_{ion} is the ionization potential and m_a is the atom mass, a strong coupling is produced and electrons are accelerated to suprathermal velocities (for surveys, see Danielsson, 1973; Sherman, 1973; Raadu, 1975). The same phenomenon may also occur at the surface of a solid grain moving through a magnetic plasma, and produce a large transfer of momentum and a significant heating of the grain (Lehnert et al., 1966; Bergström and Hellsten, 1976).

I.3.4. TURBULENCE

Turbulence of a fluid is generally defined as a state where the velocity of the medium is *truly random and disordered* (see, e.g., Tsytovich, 1977). This means that the instantaneous velocity that is measured at any point in the turbulent region is non-reproducible. It is often claimed that turbulence is a very important phenomenon in cosmical plasmas. The study of the magnetosphere by *in situ* measurements has not given any indication that a large-scale turbulence is of importance. On the contrary, modern models are highly structured (see, e.g., Heikkila, 1972) in a way which excludes the existence of large-scale turbulence. Certainly, spacecraft measurements of density, magnetic field, and plasma velocity often show rapid variations. This is especially the case when the spacecraft passes magnetic field lines going through the auroral zone, the magnetopause or the neutral sheet in the tail. However, these variations seem usually to be due to current filaments or current sheets, often forming a regular pattern, which excludes the existence of at least large-scale turbulence.

The region of the terrestrial atmosphere up to the turbopause at about 100 km is often in a highly turbulent state. At still greater heights, in the ionosphere, we often find – especially in the auroral zone – rapid and irregular variations. In part these are due to convection produced by local heating, but at least in the upper ionosphere they seem mostly to be due to rapid changes in the current pattern, and secondary effects of this. It is misleading to identify them as being due to 'turbulence' in the proper meaning of the term.

The solar atmosphere is generally characterized by filaments – e.g., prominences, spicules, and coronal streamers. If a spacecraft could be sent through these regions, it would register rapid and seemingly irregular variations in density, temperature, and magnetic field. From a study of the records one would be tempted to conclude that the upper solar atmosphere were in a turbulent state. Visual observation of the filamentary structure excludes this interpretation. Certainly the filamentary structure often changes rapidly, but not in a way which makes it possible to speak about 'turbulence' in the proper sense of the word.

However, it is quite possible that the convective layer in and below the photosphere can be described in terms of turbulence.

The so-called 'shock front' on the sunward side of the magnetosphere is often thought to be in a turbulent state. There is no doubt that spacecraft traversing it register irregular and rapid variations in density, temperature, and magnetic field. When passing the 'shock front' the solar wind slows down, and as it consists of a

collisionless plasma this can be done only by electromagnetic forces acting on the particles. There is no doubt that in the 'shock front' region there is a network of rapidly varying electric currents which interact with the magnetic fields partially produced by themselves, but it is not at all evident that this should be referred to as 'turbulence'. In fact, it is misleading to use this term for a phenomenon which has very little similarity with, for example, the tropospheric turbulence.

The distinction between 'turbulence' and 'rapid apparently random fluctuations' is not only a semantic question. Turbulence is usually associated with mixing. In the turbulent region below the turbopause there cannot be any appreciable difference in chemical composition because of the mixing which is a result of turbulence (see, e.g., Rishbeth and Garriott, 1969). A similar mixing does not necessarily take place in a region with a filamentary structure. On the contrary, there is evidence for the opposite.

In the solar wind there are large variations in the He/H ratio (between $<1\%$ and 20%) – see, e.g., Hirschberg *et al.* (1972) – and this is likely to be due to a chemical separation by plasma processes (e.g., due to difference in ionization voltage). Such processes are, of course, impossible if the region were in a turbulent state with associated mixing.

There are many phenomena in cosmical physics which are attributed to turbulence. For instance, line broadening is often interpreted in such a way. As we have found, there is no clear evidence that turbulence is of importance in the low density space plasmas which so far have been explored by *in situ* measurements. On the contrary, it seems that magnetic fields give a structure to low density plasmas which suppresses or prevents turbulence. A perturbation is more likely to produce hydromagnetic waves than turbulence. In fact it seems that most of the fluctuations in the magnetosphere and solar wind can be accounted for as a superposition of hydromagnetic waves (Belcher and Davis, 1971; Hollweg, 1975).

It is reasonable to conclude that also in regions which are not yet accessible to *in situ* measurements there is no pronounced turbulence. Hence, speculations attributing various effects to turbulence should not be taken seriously unless decisive arguments for the existence of turbulence have been presented. The careless habit of using 'turbulence' for 'apparently random fluctuations' should be abandoned.

I.3.5. CHEMICAL SEPARATION

Far from being mixed through turbulence cosmic plasmas have a tendency to produce large variations in the chemical composition. One mechanism is due to the different laws of motion of the non-ionized and ionized components of a magnetized plasma. a well-established example of this is the large variation in the He/H ratio of the solar wind. The condensation of non-volatile substances to grains constitutes another separation mechanism. These and other mechanisms jointly produce the large variations in the chemical composition of planets and satellites (Alfvén and Arrhenius, 1976, Chapter 20). It is possible that similar mechanisms also produce the observed

variations in the chemical composition of stars (or at least their surface layers which, of course, are the only parts we can observe).

I.3.6. IONIZING PROCESSES

Ultraviolet starlight is the main source of ionization in the Strömgren H II regions. Also, in the H I regions it ionizes elements with low ionization potentials. This has led to the belief that it is the *only* ionizer (in rare cases supplemented by cosmic radiation) and that in dark clouds where starlight is absorbed (and also cosmic radiation) the ionization may go down to zero, or in any case to very low values. This is not necessarily correct, because in many cases most ionization of a cosmic plasma is produced by a hydromagnetic transfer of kinetic or gravitational energy into electric currents which ionize.

This is obvious from a study of our close surrounding. The solar light ionizes the dayside ionospheres of the planets, but with the exception of these very tiny regions almost all ionization in the solar system is produced in other ways. The nightside ionosphere and the auroral zones are ionized by the impact of charged particles from the magnetosphere and partly also from electric currents (e.g., the auroral electrojet). The magnetosphere is ionized by energy transfer from the solar wind, which in turn derives its kinetic energy, temperature, and ionization from the hot solar corona and probably at least partly from electric currents in the close environment of the Sun. The corona is heated and ionized by waves and currents which are produced by transfer of hydromagnetic energy which in turn derives from convection in the Sun. All this long chain of processes is almost completely independent of the light which the Sun emits. If the light emission (including ultraviolet light) of the photosphere were shut off, the state of ionization in the solar surroundings, including the upper parts of the solar atmosphere, would remain the same – with the exception of the small regions mentioned above.

Similarly, the high degree of ionization in the Jovian magnetosphere has very little to do with the light emission from the Sun or from Jupiter.

Hence we see that almost all ionization in our surroundings does not derive from ultraviolet light (or from cosmic radiation) but from hydromagnetic effects which drain their energy from the kinetic energy mostly released in the solar convection zone. We know enough about this rather complicated chain of transfer of energy from the source to the ionization in our surrounding to be able to follow it at least in general.

Applying these conclusions to the formation of stars, we should note that the formation of a star from a dark cloud represents a release of gravitational energy of the order of several thousand times the sum of the ionization energies of all the atoms in the whole mass. As the hydromagnetic transfer in general is a rather efficient process, we can conclude that the processes we have discussed are likely to produce a rather high degree of ionization during formation. Although a quantitative analysis

of the transfer processes is difficult to carry out in detail, we can be sure that there is enough ionization to exclude a pre-hydromagnetic treatment of star formation. Of course, this does not exclude the fact that there are partial processes – e.g., the drift of dust and the formation of stellesimals – which can be treated essentially without the introduction of hydromagnetic processes.

I.3.7. DUSTY PLASMAS

We have stressed in the preceding paragraphs that the only sensible way of treating plasma phenomena in regions which are far from us in space or time is to start from the properties of plasmas explored in the laboratory and by *in situ* measurements in space. However, there are some limitations to this approach. Contrary to the situation in magnetospheric and heliospheric plasmas, dust can often be expected to play an important role in interstellar plasmas. In some cases it may therefore be difficult to approach galactic phenomena exclusively through extrapolation of the plasma properties which we now begin to know reasonably well in the magnetosphere and heliosphere. A systematic and thorough analysis of the general properties of dusty plasmas has not yet been made, but some of the problems we encounter can already be understood by a qualitative discussion.

Solid bodies in space, including dust grains, are usually electrically charged in relation to the surrounding plasma, as pointed out especially by Spitzer (1968). There are two competing effects: photoelectric emission, which gives the solid body a positive charge, usually of a few volts, and the ambipolar diffusion which gives a negative charge, usually a few times the volt equivalent of the electron temperature in the plasma. In plasmas with a temperature not exceeding some 10 000 K, the charge is also in this case of the order of a few volts. Whether the grain is positively or negatively charged depends on which of these effects predominates. However, a space plasma often contains a considerable number of superthermal electrons which, under certain conditions, may give a solid body negative potential of several thousand volts (de Forest, 1972; Reasoner *et al.*, 1976). Sudden changes between a few volts and several thousand volts have often been measured on spacecraft orbiting the earth.

If a very small grain is electrically charged, electromagnetic forces may dominate its motion so that it can be considered as part of the plasma. The condition for this is that $\mathbf{f}_m = q\,(E + \mathbf{v} \times \mathbf{B})$ (where q is the charge and $\mathbf{v}$ the velocity of the grain) is larger than other forces such as gravitation, light pressure and the viscous interaction with the other constituents of the plasma. If the dust content of a cloud is large enough, most of the electrons in the plasma may be absorbed by the dust. In an extreme case the plasma may consist of heavy negative particles (dust) and less massive, positive particles (positive ions) contrary to ordinary plasmas with light negative and heavy positive particles.

Dust in space usually consists of particles with a large variety of masses. The light particles are part of the plasma, whereas for the heavy particles the electric charge can be neglected so that their motion is determined by non-electromagnetic forces. In

an intermediate mass range there may be sudden transitions if the particles are suddenly charged up from a few to some thousand volts. Some of the problems associated with dusty plasmas have been discussed by Alfvén and Arrhenius (1976), but we are still far from a general understanding of their complicated properties.

PART II
HYDROMAGNETICS OF COSMIC PLASMA CLOUDS

II.1. Electromagnetic Pressure Effects

It is usually believed that hydromagnetic effects *counteract* the contraction of a cosmic cloud. This conclusion is, however, model dependent. It is easy to find magnetic configurations in which the contraction is *assisted* by electromagnetic *forces*. Such forces may even be decisive for the formation of cosmic clouds, and for keeping them together.

The pressure gradient ∇p which is produced by stationary electromagnetic phenomena is

$$\nabla p = \mathbf{i} \times \mathbf{B}. \tag{II 1}$$

As

$$\mathbf{i} = \frac{1}{4\pi} \nabla \times \mathbf{B}, \tag{II 2}$$

we can eliminate either $\mathbf{i}$ or $\mathbf{B}$. In cosmical plasma physics traditionally $\mathbf{i}$ is eliminated, which gives

$$\nabla p = \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B}, \tag{II 3}$$

or

$$\nabla \left(p + \frac{B^2}{8\pi} \right) = \frac{(\mathbf{B}\nabla)\mathbf{B}}{4\pi}. \tag{II 4}$$

Under certain assumptions (for example, if all magnetic field lines are parallel) the right-hand term is zero and we have

$$p + \frac{B^2}{8\pi} = \text{const.} \tag{II 5}$$

The general belief that a magnetic field counteracts the contraction of a cloud is essentially based on this formula, which is not generally valid. In order to illustrate the importance of the right-hand term we shall treat a simple case in more detail (Rose and Clark, 1961).

Consider a cylindrical coordinate system (r, Φ, z) and suppose that the variables (pressure p, magnetic field $\mathbf{B}$, and current density $\mathbf{i}$) depends only on r. Then we have, from Equation (II 1)

$$\frac{\mathrm{d}p}{\mathrm{d}r} = i_\Phi B_z - i_z B_\Phi.$$
(II 6)

With $B_\Phi = (2/r)I_z(r)$, where $I_z = I_z(r)$ is the total current in the z direction inside a circle with radius r, and

$$i_\Phi = -\frac{1}{4\pi}\frac{\mathrm{d}B_z}{\mathrm{d}r}, \; i_z = \frac{1}{2\pi r}\frac{\mathrm{d}I_z}{\mathrm{d}r},$$

we find, from Equation (II 6),

$$\pi r^2 \frac{\mathrm{d}}{\mathrm{d}r}\left(p + \frac{B_z^2}{8\pi}\right) = -\frac{1}{2}\frac{\mathrm{d}(I_z^2)}{\mathrm{d}r}.$$
(II 7)

After integration by parts we obtain

$$-\pi r_1^2\left(p + \frac{B_z^2}{8\pi}\right)_{r=r_1} + \int_0^{r_1}\left(p + \frac{B_z^2}{8\pi}\right)2\pi r\,\mathrm{d}r = \tfrac{1}{2}I_z^2(r_1).$$
(II 8)

II.2. Three Special Cases

We have three important special cases:

1. $i_z = 0$. The current flows only in the Φ-direction (see Figure 2(a)) and Equation (II 8) is satisfied by

$$p + \frac{B^2}{8\pi} = \text{const}.$$
(II 9)

The sum of the gas pressure and the 'magnetostatic pressure' is constant in space.

2. $p = \text{const}$. The field is force-free. From Equation (II 6) we obtain

$$\frac{i_z}{i_\Phi} = \frac{B_z}{B_\Phi}.$$
(II 10)

This leads to a spiralized magnetic field (Figure 2(b)) which is parallel to the z-axis at $r = 0$, but perpendicular to it at large r values (Murty, 1962). For large r values, B_Φ decreases in proportion to r^{-1}.

3. The third case is given by the conditions $B_z = 0$ and $p(r_1) = 0$. This is equivalent to the classical pinch with an azimuthal magnetic field and currents in the z-direction (Figure 2(c)). In a fully ionized plasma having temperature $T_i = T_e = T$ and density $n_i = n_e = n$ and with $N = \int_0^{r_1}(n_i + n_e)2\pi r\,\mathrm{d}r$ (=total number of ions and electrons per unit length), we obtain from Equation (II 8) the Bennett relation (Bennett, 1934)

$$I_z^2(r_1) = 2Nkt.$$
(II 11)

Even if the gas pressure is zero outside r_1 we can confine a plasma inside r_1.

When a plasma is only partially ionized, the electromagnetic forces act on the non-ionized components only indirectly through the viscosity between the ionized and non-ionized constituents. If the coupling is strong we should add a term $2N_A k T_A$ in Equation (II 11).
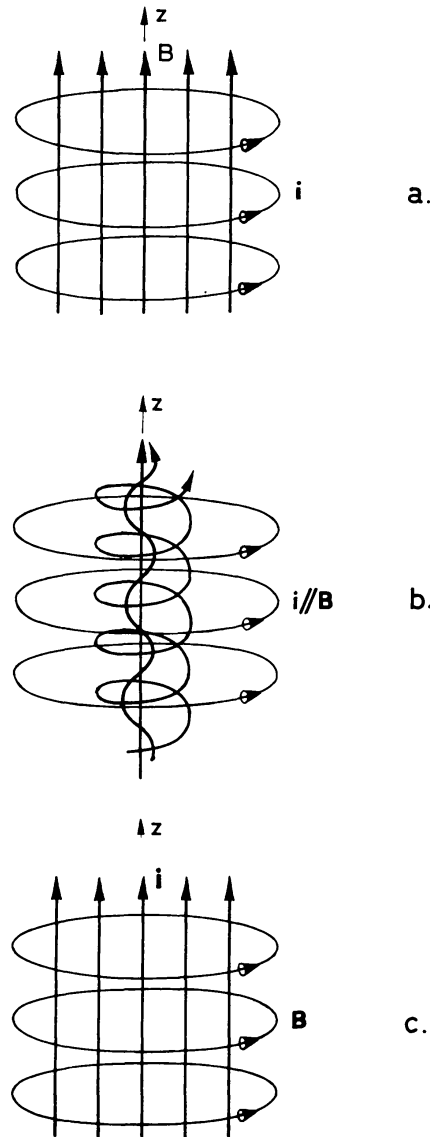

Fig. 2

Fig. 2. Three special cases of stationary and cylindrically symmetric current (**i**) and magnetic field (**B**) configurations. Part (a) shows a toroidal current and an axial magnetic field leading to an electromagnetic force which is directed radially outwards. The sum of the gas pressure and the 'magnetostatic pressure' is constant in space. Part (b) illustrates a force-free configuration with **i** and **B** parallel. Part (c) shows the Bennett pinch with an axial current and a toroidal magnetic field. Even if the gas pressure is zero outside a certain radius, the plasma can be confined inside the radius if the current is sufficiently large.

II.3. Force-Free Magnetic Fields and the Production of Filaments

We now consider a plasma which is penetrated by a nearly force-free magnetic field and current forming a spiral structure similar to that shown in Figure 2(b). The plasma is assumed to have a high but not infinite conductivity. This implies that an electric field E_z has to be present. At a large radial distance r from the axis the magnetic field is almost toroidal and of magnitude $B_\Phi = 2I_z/r$, where I_z is, as before, the total current in the axial direction inside r. Under the influence of the electric field there is an inward radial drift

$$v_r = -\frac{E_z}{B_\Phi} = -\frac{E_z}{2I_z} r. \tag{II 12}$$

Hence, if at a large distance r the mass density is ϱ, the filament sucks in matter at the rate

$$\frac{\mathrm{d}M}{\mathrm{d}t} = 2\pi r v_r \varrho = \pi r^2 \varrho \frac{E_z}{I_z} \tag{II 13}$$

per unit length.

If the electric field is antiparallel to the current, the drift is directed outwards.

Filaments are observed in the solar corona. Prominences and spicules are likely to be of the same character. Interstellar clouds often show a filamentary structure, indicating that currents flow along the magnetic field lines.

II.4. Do Magnetic Fields Aid or Counteract a Compression?

If the magnetic field is force-free it neither aids nor counteracts a contraction. The condition for this is that the electric currents producing the field flow parallel to the magnetic field. In the case of a cylindrical geometry the field lines, as well as the current lines, are spirals of the type shown in Figure 2(b). If we change the angle between the current lines and the magnetic field lines from zero in the force-free case to a finite value so that the current (i_1 in Figure 3) becomes more toroidal than the magnetic field, the electromagnetic pressure acts in the outward radial direction so as to counteract a contraction. If, on the other hand, the current (i_2 in Figure 3) becomes more axial than the magnetic field, the electromagnetic forces tend to pinch the plasma.

Hence, decisive for the question of whether a magnetic field of cylindrical symmetry compresses or dilates a plasma, is whether the magnetic field is or is not more toroidal than the electric current.

In the magnetosphere both parallel and perpendicular currents are observed. The auroral current system consists of magnetic field-aligned currents (Birkeland currents) which close through currents perpendicular to the magnetic field (Boström, 1975; Zmuda and Armstrong, 1974; Alfvén, 1977a). Hence, these currents are largely
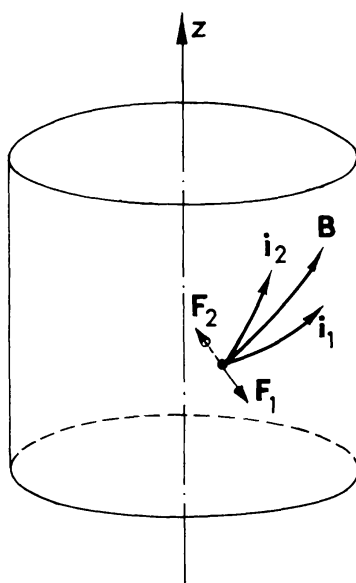
Fig. 3. Current and magnetic field configuration with axial and toroidal components only. If the current (i_1) is more toroidal than the magnetic field, the electromagnetic force $F_1 = i_1 \times B$ is directed radially outwards. If the current (i_2) is more axial than the magnetic field, the force $F_2 = i_2 \times B$ is directed radially inwards.

perpendicular to the magnetic field in the ionosphere and in the equatorial plane, and parallel in the highest parts of the ionosphere and in most of the magnetosphere except near the equatorial plane. The current is large enough to change the motion of the plasma, but not large enough to change the magnetic field very much at distances from the earth of less than 5 R_E. At larger distances the magnetic field is essentially given by the current pattern. This is the case both at and outside the magnetopause, and in most of the magnetotail.

In the solar atmosphere there are also parallel and perpendicular currents. The currents are strong enough to produce pinches. In fact, both solar prominences, spicules, and coronal streamers seem to be due to electromagnetic contraction (Alfvén, 1963; Carlqvist, 1969).

The large heliospheric current system, which according to measurements carries 3×10^9 A, flows in interplanetary space mainly in a neutral sheet in the equatorial plane where it reverses the magnetic field (Alfvén, 1975b, 1977a). What earlier was referred to as the 'sector structure' of the interplanetary field is now known to be due to the waving motion ('ballerina effect') of the current sheet (Rosenberg and Coleman, 1969; Smith et al., 1976). The current must close through currents parallel to the magnetic field in the polar regions of the Sun, but such currents have not yet been directly observed because there has not yet been any high (heliographic) latitude spacecraft mission. It is likely that the coronal streamers and polar plumes are produced by pinches in the current system. In fact, if we estimate the number of coronal streamers to be 30 (for the order of magnitude), each of them should carry

$\approx 10^8$ A. If the temperature $T = 10^6$ K is inserted into the Bennett relation (II 11) we find that the total number of ions and electrons should be $N = 4 \times 10^{23}$ cm^{-1}. If the streamer has an area of cross-section of 10^{17}–10^{19} cm^2, this means a density of $n = (4 \times 10^4)$–(4×10^6) cm^{-3}, which perhaps is acceptable.

As pointed out in the paper by Alfvén (1977a), there may be a galactic correspondence to the heliospheric current system. If we take $B_G = 10^{-5}$–10^{-6} gauss as a typical galactic magnetic field and $l_G = 10^{22}$–10^{23} cm as a typical galactic length, the galactic current should be of the order $I_G = B_G \times l_G = 10^{16}$–$10^{18}$ e.m.u. $= 10^{17}$–10^{19} A (Alfvén, 1977b). In analogy with the heliospheric current system, this current might flow in the plane of symmetry of the galaxy, possibly waving up and down. It may consist of a number of more or less confined current regions.

II.5. Pinch Compression of Dark Interstellar Clouds

In order to illustrate the possible importance of the pinch effect on interstellar clouds we shall investigate two clouds of different mass.

1. Consider first an interstellar cloud of 100 solar masses, $M_C = 2 \times 10^{35}$ g, occupying a volume of the linear dimension $l_C = 10^{19}$ cm. The temperature of the cloud is $T_C = 10$–10^2 K. This represents a cloud of approximately the same mass as the Orion nebula. The number of atoms present in the cloud is $\approx 10^{59}$, implying a mean density of $\bar{n} = 10^2$ cm^{-3} and giving $N = 10^{40}$ atoms cm^{-1}. Putting this latter figure and the temperature above into the Bennett relation (II 11) we find that an electric current of $I_C \approx (5 \times 10^{12})$–$(2 \times 10^{13})$ e.m.u. $= (5 \times 10^{13})$–(2×10^{14}) A has to flow through the cloud in order to produce a considerable compressional effect.

2. Consider next a cloud of one solar mass only, $M_C = 2 \times 10^{33}$ g, having a temperature of $T_C = 10$–10^2 K and an extent of $l_C = 10^{18}$–10^{19} cm. Hence, $\bar{n} = 1$–10^3 cm^{-3} and $N = 10^{38}$–10^{39} atoms cm^{-1}. The current needed to compress the cloud is now found to be $I_C = (5 \times 10^{11})$–(5×10^{12}) e.m.u. $= (5 \times 10^{12})$–(5×10^{13}) A.

The electric currents obtained in the above two examples of interstellar clouds seem to be a fair geometric average between the heliospheric and galactic currents. In fact, if we assume the galactic current to be distributed uniformly along a circumference of 10^{23} cm, the current through a sector of 10^{18}–10^{19} cm, should be 10^{12}–10^{15} A. Further, the magnetic field in the cosmic cloud should be of the order of $B_C = I_C/l_C$, which gives $B_C = 10^{-5}$–10^{-7} gauss, also an acceptable range of values.

In the two examples above the interstellar clouds were assumed to be contracted by a Bennett pinch, implying a pure toroidal magnetic field and a pure axial current. According to the discussion in Section 11.4, all magnetic configurations ranging from this kind of pinch to the force-free states would also give rise to contractive forces. For the plasma to pinch in these cases the total current must be larger than that given by the Bennett relation (II 11). In conclusion we can state that there seems to be no obvious quantitative objection to the capability of the pinch mechanism to compress interstellar plasmas into dense clouds.

PART III
STAR FORMATION IN A DUSTY PLASMA CLOUD

III.1. General Approach

According to the conventional view, star formation is due to a Jeans collapse of a massive interstellar cloud. The difficulty associated with a cloud of less than 100–10 000 $M_\odot$ have led to the invention of complicated mechanisms which are supposed to fragment the collapsing cloud. So far no convincing arguments have been presented for a star formation in this way. Among other difficulties it does not lead to the formation of a planetary system around the newborn star without a number of *ad hoc* assumptions. The real argument for spending so much work on the Jeans collapse seems to have been that no other mechanism has been seriously suggested.

As an alternative to these views we shall here try a new approach based on the following three principles.

1. Cosmic plasma physics should not be based on an obsolete formalism but on what is known about the properties of a plasma from laboratory experiments and *in situ* space measurements.

2. Interstellar clouds are not necessarily contracted and kept together by gravitation. Magnetic fields of the type which is observed in the magnetosphere and heliosphere are likely to exist also in interstellar space. In the same way as in our neighbourhood, they will collect gas and compress it. In this way gas clouds of any size may be formed, even so small that self-gravitation cannot keep them together. As we have found in Part II, the electric currents necessary for such pinching are not excessive. In fact they are reasonable extrapolations from currents which have been measured in the heliosphere.

3. Even if not kept together by gravitation, a cloud of dusty plasma is gravitationally unstable in the sense that dust is collecting at the centre of gravity. A dust ball is formed, which by its gravitation speeds up the sedimentation of dust, and – in a later phase – also accretes gas from its surroundings.

We have discussed (1) in Part I.

In Part II we have treated a cylindrical cloud carrying a current, and found that the magnetic field under certain conditions gives a compressional force directed towards the axis. In an idealized case this should lead to an infinite cylinder of compressed gas, but such a configuration is obviously unstable. In reality it is likely to break up in a chain of clouds in each of which one or several stars may be formed.

III.2. Motion of Dust in a Plasma Cloud

The motion of a solid particle in a plasma obeys the equation

$$m \frac{d\mathbf{v}}{dt} = m\mathbf{g} + q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \eta\mathbf{v} + \mathbf{f}, \qquad \text{(III 1)}$$

where q is the electric charge of the particle, $-\eta\mathbf{v}$ is due to viscosity, and $\mathbf{f}$ the sum of other forces, including the radiation pressure.

Depending on the size of particle, we have three typical cases.

1. *Very small particles*

The term $q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ dominates over $m\mathbf{g}$ and the particle is part of a dusty plasma.

Under cosmic conditions this is true if the size of the particle is $\leqslant 10^{-6}$ cm (Alfvén and Arrhenius, 1976, Chapter 5.4). In the case of large electric charges (cf. Section I.3.7), the limiting size may rise to 10^{-5} cm.

2. *Large solid bodies*

For 'particles' of the size of kilometres or more, the inertia and gravitational terms dominate. Electromagnetic forces are completely negligible, and viscous forces can be considered as perturbations which may change the orbit slowly. Depending on the properties of the cosmic cloud, viscous forces become important for metre or centimetre sizes.

3. *Grains*

If the size of the particle is so large that the electromagnetic term is negligible, we have an intermediate case dominated by viscosity and gravity. The particles in this regime shall here be referred to as 'grains'. Their equation of motion is

$$\eta\mathbf{v} = m\mathbf{g}. \tag{III 2}$$

Under the conditions in interstellar clouds this may be valid for particles of, say, 10^{-3} cm and a few orders of magnitude around this value.

III.3. Sedimentation of Dust in a Gravitational Field

Even if a dusty plasma cloud in interstellar space is kept together mainly by electromagnetic forces, the gravitational field of the cloud may play an important role for the motion of grains and large solid bodies. Horedt (1976) has pointed out that the gravitation of the cloud causes dust to collect at its centre of gravity where a 'proto-core' is produced which may develop to a star by collecting the surrounding gas. The Horedt mechanism is probably only one of many instabilities which may lead to star formation long before the Jeans condition is reached. Its basic properties can most easily be illustrated by the following simple model.

We consider a dusty cloud of constant density ϱ which, at a distance $\mathbf{R}$ from its centre of gravity, gives rise to the gravitational acceleration

$$\mathbf{g} = -\frac{4\pi}{3}\varrho G\mathbf{R}, \tag{III 3}$$

where G is the gravitational constant. A spherical dust grain of radius r, density θ, and mass $m = 4\pi\theta r^3/3$ is then acted upon by the gravitational force

$$\mathbf{f}_g = m\mathbf{g} = -\left(\frac{4\pi}{3}\right)^2 G\varrho\theta r^3\mathbf{R}. \tag{III 4}$$

If the grain moves with the velocity $\mathbf{v}$ through the gas of the cloud, having temperature T and mean molecular mass m_m, it is also acted upon by a viscous force

$$\mathbf{f}_v = -\frac{4}{3}\pi r^2\varrho\frac{2}{\sqrt{\pi}}u_{\text{th}}\mathbf{v}, \tag{III 5}$$

where $u_{\text{th}} = (2kT/m_m)^{1/2}$ denotes the mean thermal velocity of the molecules (see William and Crampin, 1971, small sphere, low speed case).

Putting $\mathbf{f}_g = -\mathbf{f}_v$ we find that $\mathbf{v} = -2\pi^{3/2}G\theta r\mathbf{R}/3u_{\text{th}}$, which means that the grains sediment towards the centre of gravity with a time constant

$$\tau = \frac{|\mathbf{R}|}{|-\mathbf{v}|} = \frac{0.27u_{\text{th}}}{G\theta r}. \tag{III 6}$$

With $G = 6.7 \times 10^{-8}$ g^{-1}s^{-2}, $\theta = 1$ g cm^{-3}, and $u_{\text{th}} = 6 \times 10^4$ cm s^{-1} (for H_2 and 50 K) we find $\tau = 2.4 \times 10^{11}\,r^{-1}$ s or

$$\tau = \frac{10^4}{r} \text{ years}. \tag{III 7}$$

From this equation we obtain the values given in Table I.

In an initially homogeneous cloud a dust ball with a radius of 10^{-10} of the initial cloud will be formed in a time $= 23\tau$. As the large particles sediment more rapidly than the small ones, a ball consisting of the largest particles in the cloud will be formed at the centre of gravity.

The small particles in interplanetary space (micrometeoroids and meteoroids) are observed to obey a size distribution function which decreases with increasing radius of the particles (see, e.g., Soberman $et\ al.$, 1974). The mass distribution of these particles, on the other hand, shows an opposite trend which means that the larger particles represent a larger integrated mass than the smaller ones.

Very little is known from direct observations about the size distribution of the dust particles in interstellar clouds. A reasonable guess is, however, that it resembles the

TABLE I

Time constant τ of sedimentation of dust particles as a function of radius r

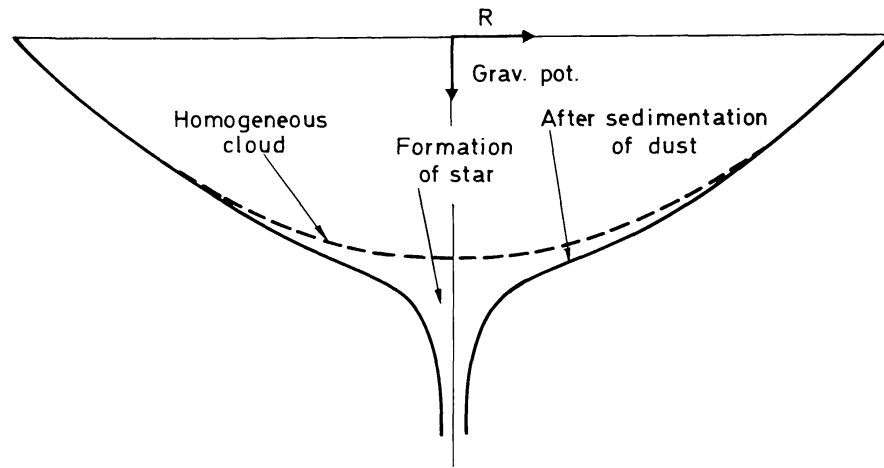| r cm	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
τ years	10^9	10^8	10^7	10^6	10^5

Fig. 4.   Gravitational instability in a dusty plasma cloud.

size distribution in interplanetary space. In that case a considerable fraction of the total mass of the dust in the interstellar cloud should be stored up in the larger particles.

Once a dust ball has formed in the cosmic cloud it will exert a gravitational attraction in its close surroundings (see Figure 4) and will speed up the further accretion so that the real time of accretion for dust of a certain size may not be larger than τ. As the accretional time depends linearly on the size of the grains, the time of accretion may be set essentially by the formation of large grains in the dusty plasma. Unfortunately the processes leading to the formation of grains in cosmic plasmas are still poorly understood.

The study of the behaviour of an interstellar dusty plasma is still in a preliminary state. The formation of dust particles of different size has not yet been properly treated because most studies start from a picture of a homogeneous non-ionized gas, which is unrealistic. Much further work in this field is necessary before we can hope to treat this phase of star formation in an adequate way.

The sedimentation process we have outlined is not likely to be prohibited by turbulence in the cloud. First of all, according to Section I.3.4, it is not very likely that cosmic clouds are turbulent. The irregular motions observed are more likely to be due to propagating waves, and these will not in general impede sedimentation. Furthermore, the nucleus of the dust ball may be formed by very large grains in a rather short time.

III.4. Formation of Stellesimals

A dust ball of mass M_D and radius R_D has an escape velocity of $v_{es} = (2GM_D/R_D)^{1/2}$. Around the ball an atmosphere with a maximum density n_m is formed out of the

surrounding cloud having a density n_0. If the temperature of the gas is constant, and if we neglect the mass of the atmosphere compared to M_D, we have

$$\ln \frac{n_m}{n_0} = \left(\frac{v_{es}}{u_{th}}\right)^2.$$ (III 8)

When v_{es}/u_{th} has reached a value of 6.5 (which occurs when the dust ball has grown somewhat bigger than the Moon, assuming a gas temperature of 100 K) we find from Equation (III 8), with $n_0 = 10^5$ cm^{-3}, a maximum density of about $n_m = 10^{23}$ cm^{-3}. A further increase in v_{es}/u_{th} cannot lead to a further drastic increase of the maximum density, because a condensation of liquid and solid substances will take place in the atmosphere (see Figure 5). The necessary result is instead a *runaway accretion* leading to a decrease in the density of the surrounding cloud. This stage of the development represents a dynamic phase, the treatment of which is beyond the scope of the present paper.

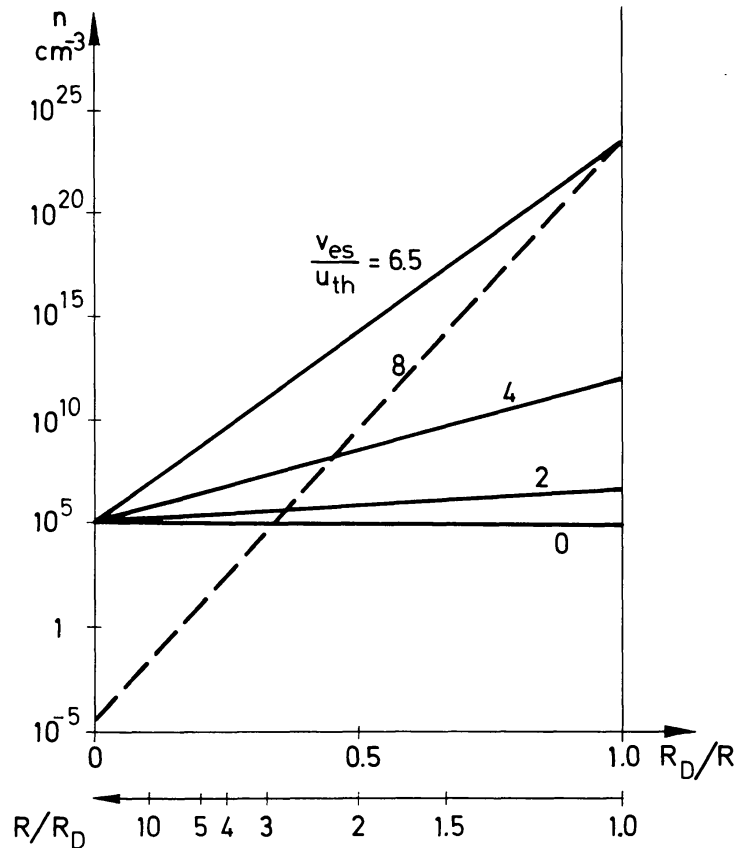For a cloud of solar mass, the critical size of the dust ball is reached when its mass

Fig. 5. Stationary density distribution in an isothermal cloud surrounding a dust ball with radius R_D and escape velocity v_{es}; u_{th} is the thermal velocity of the gas molecules in the cloud. When v_{es}/u_{th} becomes larger than ≈ 6.5, the gas condenses into liquid and solid substances near the surface of the ball and stationary solution is no longer possible. The result is a runaway accretion.

is about 10^{-6} of the mass of the cloud. From now on we will refer to the dust ball as a 'stellesimal' (analogous to a 'planetesimal').

A non-rotating and non-magnetized cloud will rapidly be completely accreted by the central body. Magnetization and rotation puts an outer limit to the region of accretion. The result is an almost void region around the body, surrounded at large distance by a partially ionized dusty plasma cloud, from which neutral gas and dust fall in towards the body. The gas falling in from a transplanetary cloud will become ionized when it has reached the critical velocity, and this will lead to a formation of planets, as we will discuss in Section III.6.

III.5. Two-Step Accretion

If the cloud is inhomogeneous, so that it can be depicted as consisting of a large number of small local clouds, stellesimals can form simultaneously in several of these clouds as a first step. The second step consists in the accretion of secondary stellesimals by the biggest stellesimal ('embryo'). The mass gain by the embryo finally resulting in a star may take place essentially through such a two-step accretional process. The intermediate stellesimals may be 10^{-6}–10^{-3} $M_{\odot}$.

In a cloud of irregular shape the stellesimals may be accreted by two or more embryos, leading to the formation of double or multiple stars.

III.6. Properties of the Early Sun and its Environment

The process of star formation we have considered leads to a condensation of most of the cloud material which originally was located inside a certain limit. Outside this there remains a rather undisturbed dusty plasma hung up on the initial magnetic field. Between this and the star there is a region with very low density, through which dust and neutral gas fall inwards towards the star. This is a situation which is acceptable as 'initial condition' for the formation of a planetary system (Alfvén and Arrhenius, 1976).

A system of secondary bodies formed around a central body is determined by the mass and the spin of the central body (*loc. cit.*, Chapter 23).

Hence the properties of the planetary system is initially determined by the mass and the spin of the primeval Sun. The solar mass is given by the mass of the condensing cloud. Its spin should be given by the accretional process which, as we have found, may be analogous to the planetesimal accretion, discussed in Chapter 13 (*loc. cit.*).

According to Chapter 9.7 there is an 'isochronism of spins' over 12 orders of magnitude from asteroids of 10^{18} g up to Jupiter of 10^{30} g. If our Sun were formed by a similar process, the isochronism might extend even three orders of magnitude more, up to 10^{33} g (cf. Chapter 25.7).

Denoting the spin period and the density of the rotating body by τ_s and θ_b respectively, we should, according to Chapter 13, expect $\tau_s \theta_b^{1/2}$ to be a constant, which has

a value around 8 hours $(g\,cm^{-3})^{1/2}$. Taking the radius of the early (D-burning) Sun to be $10^{12}\,cm$ (cf. *loc. cit.*, Chapter 25) we find $\theta_b = 5 \times 10^{-4}\,g\,cm^{-3}$. From the isochronism of spins we should expect a period of $8(5 \times 10^{-4})^{-1/2} = 360$ hours $= 15$ days. This value should be corrected for the non-homogeneous density distribution and for the possibly complicated evolutionary history of the Sun. We should not expect such a correction to exceed a factor of 2.

According to Chapter 25.6, there is some indication that the initial period was about 20 days, which is reconcilable with the value we expected. The theory of planetesimal accretion is still in a very primitive state, and the isochronism is only an order-of-magnitude relation. However, the agreement makes it interesting to make a general analysis of the planetesimal–stellesimal accretion.

The stellesimal accretion does not conserve the magnetic flux of the initial dusty plasma. The primeval Sun should become magnetized by the same kind of hydro-magnetic process in its interior as is causing the planets to be magnetized. (We need not here discuss the controversial theories of planetary magnetization, but simply take the magnetization as an empirical fact.)

When the magnetic field of the Sun controls a region extending outside Pluto's orbit, the processes considered by Alfvén and Arrhenius (1976) will produce our solar system. The transplanetary region, studied in Chapter 19, may be identified with the rest of the dark cloud out of which the Sun once was formed. Long period comets and meteoroids may be a very tiny rest from the stellesimal era.

No formation of planets could take place before the stellesimal accretion was essentially finished, in the same way as the satellite systems could not be formed before the planetesimal accretion was over. The surprisingly high regularity of the main asteroidal belt shows that since it was formed, there cannot have been any high eccentricity celestial body large enough to disturb it.

III.7. Conclusions about Star Formation

1. The usual conclusion that magnetic fields necessarily counteract the collapse of an interstellar cloud is model dependent. In other, and at least equally reasonable magnetic field models, the magnetic field compresses the cloud. It is possible that dark clouds are formed and kept together by electromagnetic effects.

2. In a dusty cloud gravitation collects the dust at the centre of gravity of the cloud. A dust ball is formed which, when it has grown large enough, collects gas from its surrounding. This process leads to the formation of a star.

3. In a cloud with irregular structure a number of such dust balls may be formed which later join by a process which is similar to the 'planetesimal' formation of planets and satellites around the Sun. Such a 'stellesimal' accretion may result in a body having the same mass and angular momentum as the primeval Sun.

4. Both (2) and (3) result in a state around the star which is reconcilable with the state which an analysis of solar system data indicates to be a likely primeval state for planetary formation.

5. The process of star formation by dust accretion works very well even for a cloud as small as one solar mass. The conventional 'gravitational collapse' is connected with great difficulty. There are neither observational nor theoretical arguments which convincingly show that it is important for star formation.

Acknowledgements

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