1. REVIEW OF COSMICAL GAS DYNAMICS

Introductory Report

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H. C. VAN DE HULST
Sterrewacht, Leiden, The Netherlands

1. To Pick up the Trail

The subject allotted to me in the program is the 'Summary of Symposia I–III: problems considered and present status of them'. Perhaps I should have been more cautious when I agreed to this title about two years ago. For it means that, if I do my job well, you will know the present status of all problems and the Symposium is finished today. However, I am sure that, no matter how I try, there will remain enough for other speakers and for other days of discussion. For this reason, in surveying the field, I shall not consciously try to avoid the topics of other speakers. Overlap will do no harm.

I should like to transmit to the new generation – and indeed 20 years *is* a generation – the spirit in which this series was undertaken. The three earlier joint IAU-IUTAM Symposia referred to in the title were (see literature list for full references):

A 1948, Paris, *Cosmical Aerodynamics*
Publication, 1951 (Editors J. M. Burgers and H. C. van de Hulst)
35 published papers and discussion sessions, 237 pages.
B 1953, Cambridge, England, *Gas Dynamics of Cosmic Clouds*
Publication, 1955 (Editors J. M. Burgers and H. C. van de Hulst)
44 published papers and discussion sessions, 247 pages.
C 1957, Cambridge, Massachusetts, *Cosmical Gas Dynamics*
Publication, 1958 (Editors J. M. Burgers and R. N. Thomas)
47 published papers and discussion sessions, 204 pages.

I shall refer to these publications below as A, B, C. For updating references I shall occasionally refer to

D 1965, *Galactic Structure* (Editors A. Blaauw and M. Schmidt).
E 1968, *Nebulae and Interstellar Matter* (Editors B. Middlehurst and L. H. Aller).
F 1967, *Radio Astronomy and the Galactic System* (Editor H. van Woerden).

In addition to these Symposium reports and edited volumes, mention should be made of monographs by Pikel'ner (1964), Kaplan (1966), and Spitzer (1968).

The aim of the first Symposium and, likewise, of the two following ones, was to make aerodynamicists acquainted with some of the intriguing astronomical objects to which their theories might be applied and to give astronomers a feel for these theories. This was a fascinating but not entirely easy task. The final discussion of the second Symposium, after the mutual teaching had had time to sink in, starts off with

Habing (ed.), Interstellar Gas Dynamics, 3–17. *All Rights Reserved. Copyright* © 1970 *by IAU*

two grave warnings to the astronomers: do not misuse shockwaves (Liepmann, B, p. 241); do not misuse turbulence (Frenkiel, B, p. 241). Conversely, the complexity of the astronomical objects was difficult to grasp for some aerodynamicists. Von Kármán makes a reasonable suggestion and immediately gets an answer explaining why this is astronomically impossible. To which answer he deftly replies: "My imagination is not handicapped by any knowledge of the facts" (B, p. 180). I have sometimes wondered if this might not be a correct description of all theoretical astrophysicists. But no, on second thoughts I don't think that in the absence of any observations even their imagination would have been bold enough to visualize such things as stars, galaxies, spiral arms, the solar corona, comets, supernovae, quasars, and pulsars. Sometimes the strange facts dazzle us for decades before they find a proper explanation, as for example the solar corona or the white light from the Crab Nebula.

Our main task is to give intelligent comments on the observed facts, assuring full consistency with whatever we know about the laws of physics. New facts seldom reduce the number of problems; they add new ones and shed new light on old ones.

2. Growth of Data Pile

I think we are all aware of the enormous progress, in the quality and quantity, of the observational data over the past decades. Entirely new avenues relevant to our discussion are:

(a) the enormous progress of X-ray astronomy and a clear start of gamma-ray astronomy;

(b) successful surveys both in the near and the far infrared;

(c) first direct measurements of Ly-α and of the ultraviolet extinction curve;

(d) detection and extensive surveys of OH and detection of interstellar H_2O and NH_3;

(e) detection and extensive surveys of high recombination lines yielding densities and radial velocities;

(f) direct space observations of cosmic rays below the GeV energy range permitting conclusions on cosmic-ray heating;

(g) three more ways to measure the magnetic field, viz. Zeeman effect, Faraday effect, and radio-continuum polarization.

I shall return to some of these points below but wish to recall first that the progress in the now 'classical' fields has also been enormous since this Symposium series was started.

The first Symposium took place several years before the 21-cm line was observed. Nothing was known at that time about the spiral arms in our Galaxy and a possible gaseous halo became a topic of discussion only in 1955 (Baldwin, 1957). The volume of the second Symposium contains as novelty several full-page reproductions from sheets of the Palomar Sky Atlas, which had not yet become publicly available (B, pp. 8, 10, and 12); to meet Minkowski's demands I personally supervised the running off of these plates at the printer.

The situation with magnetic fields was amusing. A month before the Symposium, Oort said to me as a young staff member: "Alfvén, who has worked so much with those magnetohydrodynamic waves, is coming and I am afraid that nobody will take up this subject. Why don't you study it a little?" I did. But the Symposium happened to be a few months after the discovery of interstellar polarization* and after Fermi proposed his mechanism for the acceleration of cosmic rays (Fermi, 1949; see also Fermi, 1954). The theorists were well aware of the possible influence of magnetic field on turbulence and shock waves. So, for several days, before it was my turn to speak, everybody had discussed magnetic fields!

Before I leave the memoirs let me try to give you a quantitative idea of observational progress. The accumulated output of the 21-cm line observations, exclusively from the Netherlands, is given below:

1953: 50 'clean' profiles with 7-m dish; first sketch of spiral arms (Van de Hulst, 1953);

1957: 700 'clean' profiles with 7-m dish; 3-dimensional map of spiral structure that has gone into many textbooks (Muller and Westerhout, 1957);

1969: some 40 000 'clean' profiles with 25-m dish (P. Katgert, private communication).

Here a 'clean' profile is the curve showing intensity versus radial velocity (frequency) at one point of the sky, obtained by averaging two to three profiles taken on different nights. The Maryland survey (Westerhout, 1969) of the strip between $b = -1°$ and $b = +1°$ alone contains the equivalent of over 10 000 profiles. With similarly impressive output from other places, the quantitative gain over 1953 is certainly larger than 1000.

In the field of optical observation, really very little was known about the distribution of faint nebulosity over the sky. I should like to mention specifically the work of the late Professor Shajn, Director of the Crimean Observatory, in photographing these nebulae and in pointing out their possible elongation in a galactic magnetic field (B, p. 37). Now, comparing the number of bits of information on the Palomar Sky Atlas, permanently available at many observatories, to the corresponding number on earlier atlases, I would estimate a gain factor 50 (image quality) × 2 (two colors) × 4 (better dynamical range) = 400.

The world number of available coudé spectra, essential in the optical study of interstellar cloud motions, has from the classical collection of Adams (300 stars in 1949) in recent years been gaining at a pace of perhaps 100 a year, again a substantial total factor, although far less than in the preceding examples owing to the time-consuming observing method.

One cannot help wondering, in each of these examples, if the progress made in the interpretation is at all commensurate with the progress in available data.

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* The announcement (Hiltner, 1949; Hall, 1949) appeared in February 1949 but at the time of the Paris Symposium in August, 1948 it was already taken for granted that the observations were not spurious.

3. Definition of Topics

So much for memoirs. We have to come to the topics and the first problem is how to distinguish one topic from another. In all sciences this problem occurs sooner or later. One can study a lot of biology before encountering the problem of how to separate animals and plants, or one can study a lot of astronomy before the difference between a star and a planet becomes an urgent problem. In interstellar gas dynamics we are faced with such problems from the outset: what is a cloud, what is the normal interstellar medium, what is a spiral arm, what is the halo? Some of these concepts have well-defined meanings in the context of a particular interpretation of a particular set of observations. Others, like 'clouds', are used with a variety of meanings.

Let us first exclude some topics. One of these is the gasdynamics of stellar atmospheres and interiors. It was found useful to discuss those at separate Symposia in Varenna, 1960 (Thomas, 1961) and Nice, 1965 (Thomas, 1967), which were also joint meetings of IAU and IUTAM.

I shall leave aside also the outermost part of the Sun, namely the solar wind or, what comes to the same thing, the dynamics of the interplanetary gas. Yet this is the only part of cosmic space now accessible to observation by direct measurements and even to experimentation. The barium cloud released on 18 March 1969 from the ESRO satellite HEOS I (see, p. 241) was at the altitude of 'only' 75000 km above the earth, i.e., barely outside the magnetosphere, but there is no technical reason why such ion diffusion experiments cannot be performed anywhere in interplanetary space. Rossi has several times pointed out that one significant reason for performing measurements and experiments in interplanetary space is that they permit us to learn more about large-scale physical phenomena, which in turn will permit us to understand better the phenomena occurring on an even larger scale in the Galaxy and in the Universe.

This relevance of interplanetary space was realized even in the pre-history of space flight. For as early as 1953 there was a clear discussion between Gold and Liepmann about the collisionless shock in interplanetary space (but not under this name, B, pp. 103–104). In the same discussion Menzel remarked: "The magnetic field of the Earth will act as a kind of 'bumper' with which the wave coming from the Sun would collide, at a distance of roughly five times the radius of the Earth" (B, p. 104). At that time this was still a completely theoretical concept, dating back to the work of Chapman and Ferraro in 1931. Now the bow shock of the Earth is a known object about which numerous experimental and theoretical studies have been made.

A third subject which I shall leave aside is intergalactic matter. There are a number of ways to estimate its density now, but no direct means for measuring its present state of motion and density fluctuations. The spatial arrangement of galaxies contains information about the state of motion at some time in the past, but in this field even speculative papers are scarce. [See, however, Ozernoi's contribution in this volume, p. 216, Ed.]

A further topic to be excluded is spiral structure in our and other galaxies. This at least was the division of subjects the IAU planned between the present Symposium and the immediately preceding one in Basel (IAU Symposium No. 38). This, of course, is a fully impossible division. For where shall we find the typical interstellar matter that does not have some relation with spiral arms? That which for convenience used to be called 'normal' interstellar space, does not exist any more. In any discussion of observations we must now be careful to specify at least whether space inside or outside a spiral arm is meant, and finer distinctions probably are required.

Furthermore the character of the motion changes (gradually or abruptly) if we approach the galatic center. Near the Sun rotation along almost circular orbits in the galactic plane predominates. Near the center, complicated expansion motions are seen in addition. These by themselves form an important topic certainly worthy of the attention of this audience, but I hesitate to include it in this review.

Finally, even in the solar neighborhood, the vertical structure across the galactic disk is not simple. Matter clearly associated with spiral arms is seen even at $z=1$ to 3 kpc (Oort, IAU Symposium No. 38), although the general estimate of 200 pc for the 'thickness of the disk' is still a good figure.

Having covered the subjects that I exclude, I now come to the subjects that must be included. Please do not be angry with me if this review seems disorganized. It is difficult to give a regular account of an irregular subject.

Before the 1953 Symposium we exchanged among the participants a dozen preparatory studies. One of these was a list of 'Problems and Suggested Solutions', which I made up from the experience gained with the first Symposium. This list was printed in the volume (B, p. 42). I started out to take this list as a guideline for the present review but it turned out to be too rigid a frame.

The same difficulty of sorting out the basic questions occurred during the third Symposium. After the confusion had been steadily rising for some days we decided to insert an unscheduled 'mid-symposium summary plus general discussion' (C, p. 994) which again reviews the toughest unsolved questions.

I have tried to sort the basic questions of this Symposium and shall briefly go over the most important problem areas in the following sections.

4. Mass Balance

This question was summarized in the form of a double one: There is interstellar gas. Why? There are young hot stars. Why?

The answer, then tentative and now generally accepted is that there is a balance, gas being used by condensation into stars and gas being replenished by various processes from stars. Without details, the numbers describing this 'mass balance' for the entire Galaxy were estimated at (Biermann, B, p. 212):

(a) loss from stars in shells or explosions 0.02 $M_\odot$ yr^{-1} (this now seems an underestimate by at least a factor 3);

(b) continuous loss from stars 1 to 10 $M_\odot$ yr^{-1};

(c) gas condensation into stars 1 $M_\odot$ yr^{-1}.

Taking 3 $M_\odot$ yr^{-1} as the correct turnover rate and 0.3×10^{10} $M_\odot$ as the total mass of interstellar gas in our Galaxy (Kerr and Westerhout, D, p. 199), the average cycle during which an atom passes from the interstellar gas into a star, and conversely, is 10^9 yr.

It is perhaps telling that neither C nor D nor E contains an updating of these estimates. Yet the subject has greatly evolved in a somewhat different context (Salpeter, this volume, p. 221). Astronomers probably are more reluctant now to assume that estimates made for the solar neighborhood hold everywhere in the Galaxy. In addition we know of other factors influencing the mass balance: An inflow from outside the Galaxy, which I estimate again at the order of 1 $M_\odot$ yr^{-1} (Oort, F, p. 279) and a strong suggestion of expulsion of mass from the galactic nucleus, of about 10^7 $M_\odot$ some 10^7 years ago (Oort, IAU Symposium No. 38), i.e., again of the same magnitude.

5. Dark Matter

Either I am too conservative, or we had pretty well grasped the problem at that time, for I can almost copy the 12 lines from the 1953 Symposium without change.

"Dark matter (dust) is mainly a nuisance for galactic research and its direct dynamical effects are almost nil, although earlier researches have made an important point of the radiation pressure on the grains. Yet the dust is possibly important as a cooling agent for the gas and as an absorber of Ly-α quanta and thus indirectly for dynamics. Further the dust is important as a tracer of

(a) structural details of gas clouds, for dust and gas go mostly together;

(b) magnetic fields, if a magnetic theory of interstellar polarization holds;

(c) relative motions of gas and dust, if a wind theory of interstellar polarization holds."

I should add now that point (a) has been discussed at great length (B, Ch. 40 and 41) until Bondi closed the 'vacuum-cleaner discussion'. Dark clouds and lanes are conspicuous both in a direct look at the Milky Way and in inspecting the finest details on the Palomar sky map. A lot of structure is made visible by the dust just as structure in microscopic images is made visible by certain dyes. Yet a judicious interpretation remains necessary. The common assumption that a dust region is automatically an H I region is not always correct, for dust has also been found in H II regions (see Mathews and O'Dell, 1969). And the earlier suspicion that very dense dust regions do not contain a proportional amount of atomic hydrogen is fully confirmed by recent measurements. How much hydrogen is still present in molecular form remains an open question.

The number of data on interstellar polarization has greatly increased and we shall definitely hear about these in the discussion about the magnetic field. Although the third theory (c) has recently been revived (Salpeter and Wickramasinghe, 1969) it seems as unlikely as ever.

6. Energy Balance

Taking 10^{-12} erg cm^{-3} = 0.6 eV cm^{-3} as the unit, we find for the solar neighborhood the well-known approximate equality of energy density in four reservoirs:

star light	0.8
random gas flow or cloud motions	6 (for $\langle V^2 \rangle^{1/2} = 14$ km sec^{-1}, 1 atom cm^{-3})
cosmic rays	1.5
magnetic field	0.4 (for $B = 3\ \mu$G).

The mechanisms of exchange and possible reasons for an approximate equipartition have often been discussed and will again come up during this Symposium. The question put forth by the organizers of the first few Symposia forms part of this problem but was posed in a more vital form: How is it at all possible that the kinetic energy in the gas is maintained? It may directly lose energy to cosmic rays by Fermi acceleration and to magnetic fields by dynamo effects and energy may be lost by radiation in cloud collisions or after thermalization by viscosity. If the turnover time is 3×10^7 yr = 10^{15} sec, the supply needed to keep these motions up is 10^{-26} erg cm^{-3} sec^{-1}.

Initial hopes were expressed to get this energy from the much richer reservoir contained in galactic rotation. Differential rotation would cause turbulence and compressible turbulence would create clouds and cloud motions. This explanation has now been dropped (Parker, C, p. 959). In astronomical terms: normal (low-velocity) objects cannot do much on their small epicycles; high-velocity objects coming from kiloparsecs nearer or farther from the center could play havoc but are just too few in number.

Later preference shifted distinctly to nuclear power as the main supply. It could be released in two forms: (1) Gently, in young OB stars causing a giant expansion and subsequent break-up of the cloud complex in which these stars were born; and (2) violently, in the explosion of nova and supernova shells. Both subjects will again be discussed here. In the earlier Symposia no agreement was reached on which contribution was most important; their sum hardly seemed sufficient to supply the demand.

Some numbers from Parker's 1957 summary (C, pp. 958–59) are:

from supernovae	10^{-30} erg cm^{-3} sec^{-1},
from novae	10^{-27} erg cm^{-3} sec^{-1} (but parceled out in quantities with too small momentum),
from OB stars	10^{-28} erg cm^{-3} sec^{-1}, whereas there is required 10^{-27} erg cm^{-3} sec^{-1} (but my estimate above is a factor 10 higher).

The situation depicted in this table, which is in essence the situation at the end of our last Symposium, is far from satisfactory. Jumping from there to the present time I hesitate to say that the present situation is now clear. I shall try to sketch some important developments.

First, many authors have tried to understand the detailed processes which occur when stellar energy is fed into kinetic energy of interstellar gas flow via an expanding H II region. The list is long but I should certainly mention Oort and Spitzer, Vandervoort, Mathews, and Lasker. In a general review of the evolution of diffuse nebulae Mathews and O'Dell (1969) conclude that the general features are well understood.

Second, attempts have been made at a careful updating of the various estimates of energy supply. The general review by Kahn and Dyson (1965) and the review of the energy supply from supernovae by Kahn and Woltjer (F, p. 117) may give sufficient clues to the recent literature.

Third, there is the highly interesting development by Parker and co-workers. They started out from a somewhat different question: What are the dynamical properties of the cosmic-ray gas in the Galaxy and how are these linked to the dynamics of the interstellar gas and magnetic fields? For those who lack the courage or time to read the original papers (I count 22 references over the three years 1966–68 by Lerche and/or Parker), there are two excellent reviews by Parker himself (1969a, b). The picture developed is that the cosmic rays form a fluid flowing with a speed $\leqslant 60$ km sec^{-1}. The combined magnetic field and cosmic rays form an unstable system in which large clouds are formed. This instability resembles gravitational instability but is much stronger. The clouds thus formed derive their kinetic energy from the gravitational potential perpendicular to the galactic plane.

About a year ago Parker (1968) discussed how the older ideas of expanding H II regions should be matched to this new picture. I must confess that I still have trouble understanding the complete picture. In this paper the 'disruptive forces' of the H II regions are described as counteracting the attractive forces which form the clouds; in the Oort-Spitzer picture, on the contrary, the H II regions are the agents which lead to compression forming the clouds. Also, I do not see how the energy balance works. Traditionally, the gas clouds were thought to oscillate like the stars back and forth across the galactic plane, constantly exchanging kinetic and gravitational energy. Parker modifies this picture, taking the energy for the motions out of the gravitational energy, but I have not yet seen from where he resupplies the energy. The rates, of course, are similar to those mentioned above, or even higher. Cosmic rays alone need a supply of 5×10^{-26} erg cm^{-3} sec^{-1}.

Perhaps I should go home to read; but being here I hope to have the benefit of a direct explanation.

7. Temperature and Density

For gas dynamics we need values of temperature and density and we also need something equivalent to an equation of state. We shall not dwell on this last point but simply recall what Burgers said in his summary (B, p. 228): "The interstellar gas, considered energetically, is not 'self-contained', but finds itself between a powerful source of energy, formed by high-temperature stars, and a sink, represented by the almost empty intergalactic space.... The majority of interesting cases are influenced by energy exchange." Further interesting cases will be forthcoming during this Symposium.

We should, however, say something about the uncertainty in the temperature and density estimates. Those in the H II regions can be relatively well determined from a variety of optical line ratios, radiocontinuum, high radio lines. $T=8000$ K and $n=10$ atom cm^{-3} are typical values. The variations are large and can often be individually determined. (See the Report by Mezger, p. 336.) A typical turnover time is 10^4 yr, in which the energy content of 30×10^{-12} erg cm^{-3} is turned over at a gain and loss rate of 10^{-22} erg cm^{-3} sec^{-1}. An H II region is like a rich man having and gaining much but spending it rapidly.

In contrast, an H I region is like a poor man for whom every bit of earning counts, who never has much and who has to spend it slowly. Typical values based on the classical work of Spitzer are: energy content 10^{-14} erg cm^{-3} turned over in 3×10^7 yr at a gain and loss rate of 10^{-29} erg cm^{-3} sec^{-1}.

I do not think the densities can be questioned much. The claim that the 21-cm line can be explained by much lower densities because of maser effect does not seem to work (Van Bueren and Oort, 1968) and the discrepancy with the Ly-α strength in some six stars may have a different explanation. On the contrary, unnoticed saturation effects caused by temperature and density fluctuations could, according to Schmidt, well cause the actual mean density to be two times the traditional average of 0.5 atom cm^{-3}.

The temperature is expected to vary because part of the heating is supposed to occur at occasional incidents called 'cloud collisions'. But it is hard to lay hands on good evidence regarding the temperature variation. The (harmonic?) average is 125 K. But in places we know T must be down to about 30 K; the best clue to this is in the width of the narrowest 21-cm absorption and emission peaks.

The fact that H I regions are susceptible to small gains also brings cosmic rays into the picture as a heating agent. The important energy range is around 10 MeV and the particles in this range have been referred to as sub-cosmic rays or as suprathermal particles. The main problem (see review by Meyer, 1969) is that they cannot be observed close to the earth because of geomagnetic cut-off and the measurements which have been made from space probes still require a correction factor between 10 and 10 000 to allow for solar wind modulation! Anyhow, it seems that this energy source is important for heating the H I regions.

If this is true, another intriguing possibility enters. Following earlier work, e.g., by Pikel'ner (1967), detailed computations have been made (Field *et al.*, 1969; Goldsmith *et al.*, 1969) of the heating and cooling in a wide range of temperatures and densities. These authors find that in a certain range the pressure may drop if the density rises. Thereby they have revived a type of condensation theory which (in a different context) received much attention in our earlier Symposia (Zanstra, B, p. 70). I quote from Burgers' summary (B, p. 231): "Zanstra has shown that there may correspond *three* values of the density to a single value of the pressure (depending on certain factors). The intermediate value of the density is unstable, but the maximum and the minimum values can co-exist, in which case a state is obtained with part of the gas condensed relative to the rest. Evidently, this possibility will be of great influence on the behavior of the gas; it can be compared with the condensation which under laboratory conditions may occur in water vapor."

In an earlier summary (Van de Hulst, 1969) I arrived at typical figures, which I here compare with numbers cited from Radakrishnan and Murray (1969) (Table I).

TABLE I

	n_e/n_H	n_H cm^{-3}	T K	nT cm^{-3}K
H I standard cloud	0.02	10	100	1000
Same, Radakrishnan and Murray		10	50	500
H II standard cloud	1	10	10^4	2×10^5
H II hypothetical intercloud gas (Spitzer)	1	0.05	10^4	1000
H I hot-phase intercloud gas (Field *et al.*)	0.2	0.05	10^4	600
Same, Radakrishnan and Murray		0.5	10^3	500

I bet there will be further modifications before this conference is over. I should like to point out that the new hot H I gas of Field *et al.* is rather similar to the hypothetical H II intercloud gas of Spitzer.

8. Close-ups

An astronomical photographer is not unlike a press photographer. He takes a shot from a fair distance and chooses carefully which part to blow up and publish. The alternative method, to get a close-up, permits less of a selection but shows better details.

The interstellar close-ups refer to objects several 100 pc away, or even closer. Let me review a few of them without observing any special order.

The Orion Nebula (distance 420 pc) is the nearest very young H II region containing the famous trapezium as exciting stars. It has been a choice object both for observers and theorists. One of the early observations is a drawing made by Huygens at Leiden in 1694. There are several experts on the more recent work at this Symposium. The only warning I should like to give is that the Orion Nebula is not typical for H II regions in general.

The giant planetary nebula in Aquarius NGC 7293 (distance 145 pc). This is not strictly interstellar matter, but it is one of the few cases where a planetary nebula is close enough to show its details well. The finest details seen are some comet-like condensations, observed by Baade, with typical diameters of 0.001 pc.

Interstellar matter in the vicinity of Nova Persei 1901 (distance 500 pc). The strong light pulse emitted by this nova has successively illuminated the wisps of interstellar matter in its vicinity up to a distance of about 50 pc. The most prominent feature is a thin sheet in front of the star. This is the only known case where the distribution in three space dimensions has been observed (Oort, 1946). The resolution is determined by the duration of the light pulse, some 20 days, or 0.02 pc.

Nearby atomic hydrogen. It is important to repeat that other so-called three-dimensional pictures are always obtained indirectly. The three coordinates of six-dimensional phase space which can be measured are the two positional components across and the one velocity component along the line-of-sight. In some cases (expanding shells, differential galactic rotation) the velocity component can be converted by a plausible model into a distance and a three-dimensional space picture emerges. This conversion, however, introduces a certain smoothing. In the 21-cm line this smoothing is caused by the random cloud velocities and leads to a resolution of the order of 500 pc in the line of sight, independent of distance. Hence, to get a detailed space distribution of the nearby hydrogen atoms by this method is completely impossible.

Nearest dark clouds. Some dozen striking dark nebulae are seen at distances of 100 to 300 pc (Lynds, E, p. 119). In the analysis of these nebulae by the time-honored method of star counts a distance resolution of the order of even 100 pc is considered quite good. Evidently this is of no use for our purpose of discussing structure.

One could think of a scheme whereby a three-dimensional map of interstellar extinction within 100 pc is made, starting from individual distances and extinction values for many stars. The uncertainty of intrinsic colors would hamper this scheme. However, with very accurate polarization measurements it can be made to work, and I still have the impression that much more can be done along the line that Behr started many years ago. In his review Verschuur will mention Mathewson's recent work in this field (see p. 150).

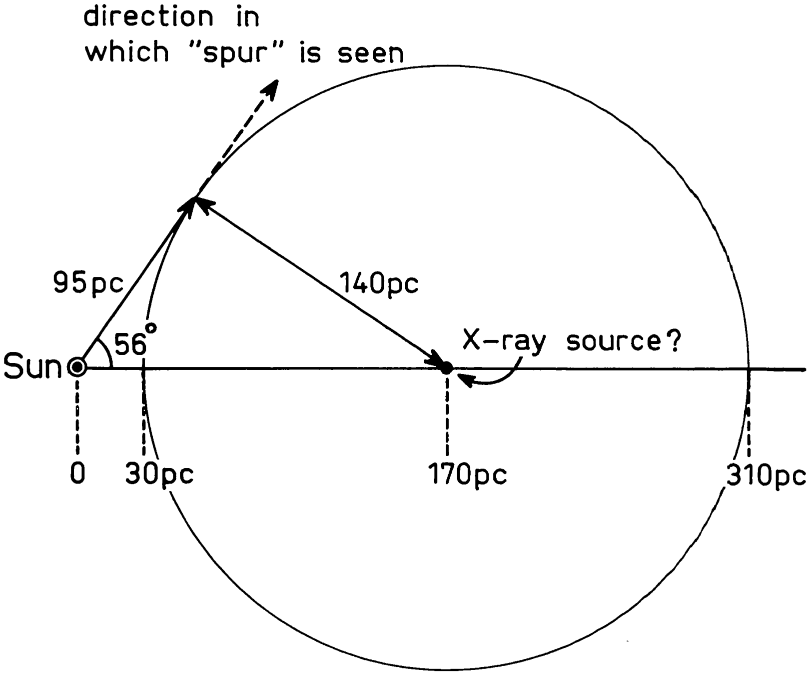

Fig. 1. Model to explain the north galactic spur and associated phenomena. Based on work by Berkhuijsen, Haslam and Salter.

The north galactic spur. This object, visible as an odd spike on the earliest radio-maps of the Galaxy by Reber, had led to many speculations about its origin and distance. There are some indications that this object may be correctly placed among the objects seen in 'close-up'. The geometry in cross-section may be about as shown in Figure 1.

The most striking feature, a roughly ring-shaped object following a small circle on the sky with radius 56° would be the locus of directions where we look tangentially to the thin shell. Enhancements in the 21-cm line at the outer edges of the ring suggest that neutral hydrogen to the amount of some $10^4 M_\odot$ is pushed ahead of it (Berkhuijsen *et al.*, 1970). Inside the shell concentric 'ridges' of continuum radiation are seen (Large *et al.*, 1966; Merkelijn and Davis, 1967); their width is of the order of $1° = 2$ pc or smaller. The short distance is mostly based on the fact that Mathewson finds a clear association between the spur and the optical polarization of stars between 50 and 200 pc. He interprets this association in terms of a helix field but it could be reinterpreted in terms of the shell model. Recently, an X-ray source has been discovered near the center of the ring ($l^{\mathrm{II}} = 332°$, $b^{\mathrm{II}} = +23°$).

All of this requires confirmation and further study but it is too attractive to be withheld in this review. Several similar but smaller arcs are known from the radio studies.

The Cygnus Loop. Other 'loops' have been observed optically. Among these, the Cygnus loop or Veil nebula (distance 500 to 800 pc) has been known from the earliest days in which photographs of the Milky Way were made. Two curved arcs very strongly suggest parts of a shell of radius $1\overset{\circ}{.}2 \approx 10$ pc. Some individual wisps in this veil have a thickness $2'' = 0.005$ pc. This object deserves special mention, because discussions between Oort and Burgers about the way to explain the compression into thin sheets as a collision effect led to the 1948 Symposium. A picture of this nebula was chosen as the frontispiece of the first Symposium (A). Minkowski rediscussed it (C, p. 1048).

9. What is a Cloud?

I return to a very central topic of the earlier Symposia. What is a cloud? The obvious answer is: a region of locally increased density. But this does not tell us much of the physics. From the point of view of the observer, 'local' could mean anything from 1000 to $\frac{1}{1000}$ pc (Van de Hulst, C, p. 922). For a gas-dynamicist *local* means any distance which can be travelled by the speed of sound within the lifetime of the object. This would make anything < 100 pc local.

The values assumed for 'standard' clouds come mostly from spectra, i.e., from a resolution in velocity space, not in configuration space. This subject has been reviewed so often that I shall not spell it out again. Spitzer's chapter in E is a very good reference. Van Woerden (F, p. 3) compares and analyzes the results obtained by some 20 authors. I summarize from his summary the values given in Table II (omitting in each case the extreme low and the extreme high estimate!). The variation may be disappointing to those who had hopes that nature would comply with their model

TABLE II

Cloud diameter	5 to 40 pc
Number on line of sight	0.7 to 11 kpc^{-1}
Mass	20 to 15 000 $M_{\odot}$
n_{H}	2 to 70 cm^{-3}
N_{H}	$(0.5\text{–}30) \times 10^{20}\ \mathrm{cm}^{-2}$
Dispersion of cloud velocities in one component	7 km sec^{-1}
Dispersion of internal velocities	0.8 to 6 km sec^{-1}
Corresponding T if internal velocities were thermal	80 to 4000K

assumptions. The actual range may be even larger, for there is some truth in the statement that the size of the smallest cloud is always equal to the resolution of the instrument. The data cited are based partly on Ca^{+} but mostly on 21-cm H lines.

Aerodynamicists may wonder what deep thought there is behind the distinction of velocities of clouds and velocity in clouds. There is none. In the analysis of the line profiles certain convenient entities are called clouds and to each cloud is assigned a speed. Whatever is then left of the velocity field is called an internal cloud motion. Most of it must have the character of gas flow because the temperatures to which this motion would correspond are too high. But if we continue to ask if the external and internal flow could be part of a continuous spectrum of turbulence, I don't think we could give a conclusive answer from these observations.

Turbulence was indeed a central topic in the earlier Symposia. It was discussed with and without compressibility, with and without magnetic fields. Gradually the views developed to consider three causes for the origin of the clouds:

(a) *Gravitational instability* is of no use for standard clouds because it starts to work effectively only at higher densities (formation of protostars) and does not lead to sharp edges.

(b) *Turbulence.* Incompressible turbulence was well explained but is not applicable to the interstellar situation. Highly compressible turbulence may be applicable. The theory is not very complete but certainly leads both to strong density fluctuations and to sharp edges. To some extent it resembles an assembly of shock waves (B, Ch. 22, 42).

(c) *Shockwaves* may form sheets, not clouds, but there is a fair chance that most of the things we call clouds are sheets. They certainly can explain sharp transitions. The sharpness of the order of the mean free path is 0.1 pc at 10 atom cm^{-3}, which is barely sufficient. However, collision-free shocks (not then known by this name) may be a great deal sharper, because the gyro-radius of an electron at 3 μG is only 10 km at 10 000 K.

We conclude that both (b) and (c) are eligible explanations but examination of the kind of energy supply (see earlier section) favors (c). But, although this answers our initial questions, we can hardly be happy with this conclusion.

Upon looking at the photographs, the sharpness of the transition between the cloud and interspace is to me as startling as the density contrast. The shockwave hypothesis may in some examples offer the explanation but in other examples the explanation may be different. We know pretty well, for instance, that the sharp transition between a dark cloud and its bright rim, which is often seen in a large H II region, is simply an ionization front. It only marks the boundary where the ionizing quanta run out and the sharpness is determined by the mean-free path of these quanta, which is 0.005 pc for a density of 10 atom cm^{-3}.

A further competitor may be spontaneous separation between 'two phases' of H I. If the theory of thermal instability, which I briefly mentioned above (see Field, this volume, p. 51), is correct, we still have to find what determines the shapes and sizes of the condensed regions and the sharpness of the transition.

Finally, I wish to point out that in any case a number of different explanations may be required because the objects are so different. Smooth 'globules' may be simple to conceive but the similarly small pitch-dark cloudlets with ragged edges (Bok, B, p. 34) are to me still quite puzzling.

There is a lot to do.

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