Several discrepancies should however be noted:

(a) the observed velocities in Barnard's loop show a small tangential component inexplicable for a spherical model except by rotation (see T. K. Menon, these Proceedings);

(b) the singular high velocity O−B stars μ Columbae, AE Aurigae, and 43 Arietis seem to originate in this Orion region;

(c) the extended HI compressed region about λ Orionis cannot be explained if cooling is efficient. Presumably an adiabatic model would be more appropriate.

In summary we have an observed motion; we have a suggestive mechanism established; we must estimate the energy input into the interstellar medium. If we assume one object of these dimensions per cylindrical volume 500 pc radius and 200 pc high per million years, we obtain an energy input of 6.9×10^{-28} erg/cm^3 sec. This figure may be improved with further 21-cm data, but it illustrates that the energy input into the interstellar medium is now an observable quantity, or at least nearly so. Figures thus derived should have precedence over estimates based upon radiation available and efficiency of utilization.

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Gas Dynamics of Galaxy Collisions

M. P. SAVEDOFF

Department of Physics and Astronomy, University of Rochester, Rochester, New York

When two galaxies collide at extremely high velocities, Baade and Spitzer[1] note that negligible stellar effects are anticipated but that the interstellar medium is violently affected. Recently the radio source Cygnus A has been identified with what appears to be two colliding galaxies. Baade and Minkowski[2] describe the optical nebula as two . . . "late-type systems, judging by low density gradients of the two disks. Spatially they are oriented face to face, they are slightly decentered, and we look upon them at an angle not far from 45°." " . . . the two systems must be in close contact because of the strong signs of tidal distortion which the nuclei show." The lines are noted as diffuse.

More recently 21-cm neutral hydrogen has been observed from this object by Lilley and McClain[3] with an almost identical velocity with that of the optical system. They estimate the mass now as $2\times10^9 A$ suns/kpc,[2] where A is the unknown area of the radio source in square kiloparsecs.

TABLE I.

Case	N	I	M
Shock velocity	−167 km/sec	−167 km/sec	−243 km/sec
Compression ρ_s/ρ_i	4	4	3.06
Newtonian sound speed $\sqrt{p/\rho}$	289 km/sec	204 km/sec	178 km/sec
Equiv. temperature	10^7 °K	5×10^6°K	3.8×10^6°K
Initial $H^2/8\pi P$	...	...	2.1×10^4
Final $H^2/8\pi P$	...	...	1
Average energy per particle	1290 ev	645 ev	490 ev

The model considered assumes we have two identical layers of gas of density $n=1$ cm^{-3}, temperature $T=100$°K, each of a width of 200 pc, and finally a relative velocity of 10^3 km/sec. These layers are presumably stabilized gravitationally against expansion. For a one Bohr radius atomic cross section, these objects are each 6×10^4 Bohr free paths thick, hence can be treated by fluid dynamics.

Kahn's treatment of this problem appears to be valid only for the first instants of mutual contact of these galaxies, if such a time has any meaning for such a diffuse collision. After about 10^8 seconds we may expect to find a compressed hot gas, taken as being at rest, containing the initial contact surface (C) between the gas derived from the two galaxies, two shocks (S) moving out into the oncoming gas, and finally the undisturbed gas coming in at 500 km/sec from either side.

Applying the Rankine-Hugoniot conditions across the shocks (or the de Hoffman-Teller[4] conditions for transverse magnetic fields) we obtain the estimates of Table I for three cases: (N) no ionization; (I) complete ionization; (M) ionization with a final magnetic pressure equivalent to the gas pressure present (includes no fields in vacuum between gas clouds).

We can estimate the rate of ionization of the hydrogen at these energies. Calculations by Bates and Griffing[5] for the reaction $H(1s)+H(1s)\rightarrow H^{+}+e+H$ permit the estimate that the cross section exceeds $0.1\pi a_0^2$ in the range 500 ev to 1000 ev. Thus collisional ionization

[1] W. Baade and L. Spitzer, Astrophys. J. **113**, 413 (1951).
[2] W. Baade and R. Minkowski, Astrophys. J. **119**, 206 (1954).
[3] A. E. Lilley and E. F. McClain, Astrophys. J. **123**, 172 (1956).
[4] F. de Hoffman and E. Teller, Phys. Rev. **80**, 692 (1950).
[5] D. R. Bates and G. W. Griffing, Proc. Phys. Soc. (London) **A68**, 90 (1955).

TABLE II. Loss in ergs/cm³/sec ($n=4$).

T (°K)	L_{ff}	L_{fb}	L_{bb}
5×10^6	5×10^{-23}	4×10^{-24}	5×10^{-25}
10^6	2×10^{-23}	9×10^{-24}	3×10^{-24}

TABLE III.

n_e (cm^{-3})	T (°K)	Surface brightness ergs cm^{-2} sec^{-1}
4	5×10^6	0.01
20	10^6	0.03

should take place within 10 Bohr free paths as compared to the total thickness of an individual cloud of 6×10^4 Bohr free paths. The next fastest process, $H(1s)+e\rightarrow H^+ + 2e$, is controlled by the rate at which electrons approach equipartition in elastic $e+H$ and $e+C^+$ collisions. Both processes indicate ionization after traveling about 10^3 Bohr free paths, which is the number of collisions needed by electrons with a velocity of 1000 km/sec to reach energies capable of producing ionization.

Temperature equilibrium is very rapidly established even at these temperatures. For example, electron-proton equipartition time as defined by Spitzer[6] varies from 7.89×10^5 seconds at the low electron temperature before interaction, to 2.20×10^{10} seconds (700 years) for near equilibrium temperatures. These estimates ignore the energy contributed to the electron gas by the ionization processes.

In contrast to the equilibrium time, the cooling times are quite long. We use the abundance table of Suess and Urey[7] as a base. To obtain an upper limit on radiation loss we further assume that all nuclei are stripped up to $Z=20$ at these temperatures (5×10^6°K) and low densities. Hydrogenic values are used to estimate the energy losses, assuming Z^2 dependence for free-free transitions and Z^4 for the free-bound and bound-bound transitions. In Table II we give radiation in ergs/cm³/sec for $n=4$, and $T=5\times10^6$°K and 10^6°K.

A pertinent time can be derived by comparing the maximum thickness of the compressed region (50 pc) with the Newtonian sound speed through the medium $(p/\rho)^{\frac{1}{2}}$. Thus for case I (above) $t=2.45\times10^5$ years. If the total kinetic energy of the gas were radiated uniformly in this time, the resulting surface brightness will be 0.388 erg/cm²/sec, which is equivalent to the surface brightness of a blackbody at 9°K.

[6] L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, Inc., New York, 1956).
[7] H. Suess and H. Urey, Revs. Modern Phys. **28**, 53 (1956).

With the data of Table II we obtain the values given in Table III. Recombinations are unlikely until the temperature falls considerably. By this time the gas will be of much lower density. It is difficult to understand how an appreciable fraction of the gas can recombine.

The gravitational self-attraction of the gas in certain cases may be important. Using the plane parallel approximation to a galaxy we would calculate that the kinetic energy of the gas equals the potential energy when it expands to a height h given by $h=v^2/4\pi\rho_s G$, where ρ_s is the matter density per unit area. For the model described above with $T=5\times10^6$°K we find:

$$h=6.7\times10^{24}\text{ cm}=7.8\times10^4\text{ pc}.$$

Thus in order for the expansion to be gravitationally limited to regions of galactic dimensions ($h=10^4$ pc) the gas must lose about 90% of its energy in the time it takes to expand to this height.

We have previously estimated that the compressed gas expands its own width (50 pc) in 2.45×10^5 years. In this time if all the energy were radiated the surface emission would be 0.388 erg/cm² sec. The calculated rate of emission from physical constants is actually only 0.01 erg/cm² sec. Although expansion to a height of 10^4 pc will take 200 times longer than expansion to 50 pc, the total emission is not 200 times that radiated in 2.45×10^5 years, but $\log_e 200=5.3$ times, if account is taken of the decreased density. We see that the physical emission processes are a factor of 7 too inefficient to permit the gas to become gravitationally bound to itself by cooling.

The observed high density of neutral hydrogen in Cygnus A and in clusters of galaxies imply that recombination does take place in contrast with the results of the calculation above. Also, no proposed mechanism is given here for the extremely efficient radio emission, nor for the double spatial maxima in the intensity distribution.

DISCUSSION

T. K. MENON, *Harvard College Observatory, Cambridge, Massachusetts:* I wish to make three comments. Earlier today Wade pointed out the existence of a dark ring around the HII region belonging to λ Orionis. I wish to bring to your attention the existence of a similar dark ring bordering the HII region which presumably belongs to the Trapezium Cluster. These rings are probably formed by radiation pressure effects in the vicinity of early type stars. This follows from an early analysis by Spitzer where he showed that, in the vicinity of early type stars, the radiation pressure effects are such that gas and dust move together and not separately. This point is being investigated at Harvard in more detail.

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The second point I want to make is regarding the expansion of neutral hydrogen around the Orion association. The variation of radial velocity of the peak of the 21-cm profiles across the Orion region was interpreted at one time as due to the rotation of the complex, superimposed on the expansion. More recent observations with the 60 ft radio telescope at Harvard seem to indicate that this variation can be interpreted more readily as a nonsymmetrical density distribution and not as a rotation. Details are being published in the *Astrophysical Journal*.

The third point is that Savedoff considers the observed expansion of neutral hydrogen as being due to an O star which has since then cooled off. In such a case, it seems to me that it would be difficult to explain the excitation of the Barnard loop. Moreover, if the coincidence of the 21-cm center of expansion and the center of expansion of the Blauuw-Morgan stars is not accidental, then, as Oort and Spitzer have shown, it is not possible to accelerate these stars to such high velocities with the energy available from a single O star. Hence, as in some other problems discussed earlier in the Symposium, we are up against a deficiency in energy to explain these observations.

R. D. DAVIES, *Jodrell Bank Experimental Station, Manchester University, Manchester, England:* There is an observational point that I think we should mention regarding the Cygnus A radio source, and that is the observation by Jennison and Das Gupta at Jodrell Bank that the radio source had two centers of emission—it was not a single region. Since the Jodrell Bank symposium in 1955, they have repeated their observations and have included phase measurements of the Fourier transform; now they are quite convinced that it is in fact a region with two centers of emission, as shown in Fig. 1. Their separation is about 90 sec of arc and their width is about 30 seconds of arc. This corresponds to a breadth of 40 kpc. The optical region is in the center and has a diameter of about 10 kpc. This is the picture I think you have to consider when trying to explain the radio emission. The absorbing neutral hydrogen will have a depth of the order of 40 kpc rather than 10 kpc.

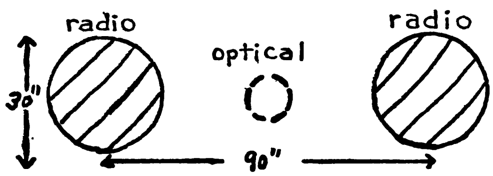

FIG. 1.

L. BIERMANN, *Max Planck Institut für Physik, Göttingen, Germany:* I would like to speak about the relation of the pattern of data now presented by Savedoff to that which I presented earlier. Attention is paid to objects of type O8 or something of that order. In comparing the data, I found that we (Schlüter and I) took as a typical star in a typical HII region, one with an energy output 20 times smaller than the one taken by Savedoff. Our star corresponds to an energy supply of 500 times the solar luminosity. In contrast, we assume that the abundance of such regions as we considered was several hundred times larger than that of the type of region taken by Savedoff. When one combines the data, they seem to lead to a difference in the total energy per gram of interstellar material and per second, converted into mechanical energy, by roughly one power of 10 above that given by Savedoff; and that is just the difference between his figure and the one I have presented. Hence, if one agrees that objects, which are not quite as exceptional as this one, are several hundred or a thousand times more abundant, that is, of the order of several hundred thousand or a million in our galaxy, then one has just the set of data I gave.

S. B. PICKELNER, *Crimean Astrophysical Observatory, Simeis, Crimea, U.S.S.R.:* I should like to add something to Davies comments about the presence of two centers of radio emission in Cygnus A. Several years ago Shklovsky discussed this question and offered the following explanation. If we have two galaxies, each with a halo, and these galaxies are in collision, the collision in the first phase refers only to the gases in the halos. The halos will be stopped, shock waves will cross them, and the halos will move apart with a velocity less than the initial one. The stars will continue to move in the initial direction. Thus, after some time we shall have two halos, and the stars will be between the halos. When we have strong shock waves, we usually observe relativistic electrons. Such relativistic electrons appear in large quantity in the Crab Nebula, in colliding galaxies and in all the cases where we have fast gas motions. In this case it may be the same.

F. D. KAHN, *Department of Astronomy, Manchester University, Manchester, England:* Is the loss of energy at radio wavelengths at all comparable with the loss of energy computed here for visual wavelengths?

M. P. SAVEDOFF, *Department of Astronomy, University of Rochester, Rochester, New York:* I do not have the data of Baade and Minkowsky directly in mind. My impression was that the total energy in the collision is about 10^{60} ergs, and the total energy in radio emission was about 10^{-41} erg/sec over the entire system.

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