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GALACTIC MOTION AS SOURCES FOR HEATING OF THE INTERGALACTIC AND INTRACLUSTER MEDIUM

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R_g is the galactic radius in kpc

V_g is the velocity of the galaxy in km/sec

M_g is the galactic mass in units of 10^{11} solar masses

R_a is the radius of accretion, defined as $2GM_g/V_g^2$

Ω is the ratio of actual ambient number density of background hydrogen (ρ_b) to 2.8×10^{-6} (Field, 1972).

h is the ratio of the Hubble Constant to 75 km/sec/Mpc

For convenience we define a parameter δ equal to R_a/R_g. This parameter measures the effectiveness of the shock mechanism as a whole.

In either the RS or Hunt models moving galaxies have several cross sections for the shock process and its associated drag: The most important are the geometrical cross section, πR_g^2 and its associated drag D_g, where

$$D_g = 1.4 \cdot 10^{29}\ \Omega\ V_g^3\ R_g^2 \qquad , \qquad (2)$$

and the accretion cross section, πR_a^2, with drag

$$D_a = D_g \cdot (\delta^2) \cdot \left(1 + \frac{V_g^2}{C_\infty^2}\right)^{-1} \qquad , \qquad (3)$$

where C_∞ is the speed of sound. Note that D_a is actually proportional to $(V_g)^{-1}$.

We can also write (3) as

$$D_a = 8.5 \cdot 10^{40}\ \Omega\ M_g^2\ V_g^{-1} \cdot (1 + V_g^2/C_\infty^2)^{-1} \qquad (3a)$$

SHOCKS IN CLUSTERS OF GALAXIES: Application to the Coma Cluster

In considering clusters we are reminded that the various dynamical parameters differ greatly from their field values. Galactic number densities, background intracluster medium densities, galactic speeds and probably gas temperatures are all larger. X-rays have been detected from various rich clusters: Gursky et al., (1971) and Gursky et al, (1972) reported nine clusters with estimated x-ray luminosities exceeding 10^{43} ergs/sec. In this section we shall discuss whether galactic shocks or galactic motions in general could be responsible for these observations, particularly in the case of the Coma Cluster.

The relevant parameters, summarized from recent data by Lea et al. (1973), indicate that a plasma of density $2 \times 10^{-3}/\text{cm}^3$ particles of hydrogen in a region around the center of Coma of extent 15' (in radius) is radiating as much as 10^{44} ergs/sec in x-rays with a thermal bremsstrahlung temperature of 12 kev (cf. also Margon, 1973). At the distance of Coma, $92h^{-1}$ Mpc, the hot region is about

$$800h^{-1} \text{ Kpc} \simeq 2.7 \times 10^{24} \ h^{-1} \text{ cm} \qquad (4)$$

across, with a spherical volume of about $1.05 \times 10^{73} \ h^{-3} \ \text{cm}^3$.

From the work of Abell (1974, private comm., also 1972) there appear to be about 100 galaxies to eighteenth visual magnitude in the hot central region of Coma. Using the kind of model for density profile as found in Rood et al. (1972), where the surface density S(r) of galaxies is given by

$$S(r) = S_o / (1 + (r/r_c)^2) \quad , \qquad (4a)$$

the three-space density can be integrated directly along a line of sight and is found to be $N(r) = N_o / (1 + [\frac{r}{r_c}]^2)^{\frac{3}{2}}$ where S(r) and N(r) are the surface-and space densities of galaxies as functions of the radial distance r, and the zero subscripts refer to the central values. The value r_c is the so-called core radius, defined in Rood, et al. (1972). In these models relating the central two-and three-space densities S_o and N_o, respectively, to their values S and N at various values of r, one can show that $S_o = 2N_o r_c$.

This in turn means that in the case of Coma about half of the galaxies seen in the central field (the radiating region) actually lie within the central $800h^{-1}$ Kpc of the center. Finally, from Rood et al. (1972) the radial velocity dispersion, and hence an upper limit to the probable three-space velocities are known: these authors calculated a dispersion of close to 1000 km/sec, giving an RMS value of $\sqrt{3} \cdot 1000$ km/sec to the velocity of a galaxy near the center of Coma.

Given these parameters, can we produce the required temperature and energy output in the intracluster medium (IGM) from galactic drag and shocks?

In the first estimate it seems that the mechanism will work. Objects with geometrical cross sections $\sim 10^{45}$ cm^2 , typical of an average galaxy, will sweep out a volume in the center of Coma equal to the known radiating volume in about 10^{10} years. The total drag from each galaxy, from Eq.(2), $\rho_b V_g{}^3 \sigma_g \sim 10^{43}$ ergs/sec gives, when multiplied by the number of galaxies in Abell's sample taking part, a heat input of about 5×10^{44} ergs/sec comparable to the observed x-ray output of this central volume of Coma.

However, most of the galaxies in Coma are ellipticals and contain little or no gas: they can only support drag bow shocks across an area given by the radius of accretion. For these parameters, with a typical galactic mass of 10^{11} $M_\odot$, we find with the aid of Eq.(3) that the time for these galaxies to sweep out the volume in question is of the order of 10^{20} sec, too long compared to the lifetime of Coma and comparable to the cooling time: some gas could be heated thusly to $10^{8°}$ K but not enough to cause x-rays in the known amounts.

For reasons also related to the small size of the radius of accretion, the RS mechanism for <u>wake</u> shocks is also ineffective. According to RS the opening angle of the wake, Θ_s, depends on the radius of accretion:

$$\Theta_s = \frac{5}{9} (\tan^{-1} [\delta(1 + \delta)^{-\frac{1}{2}}]) \sim \frac{5}{9} \delta, \text{ for } \delta << 1. \quad (6a)$$

This means for high speeds (almost independent of Mach number) particles enter the wake shock at a very oblique angle and suffer little compression or change in momentum. The temperature behind the wake shock, which depends both on the angle which particles make with the shock, θ_i, and on V_g, is, according to RS:

$$T \sim [\frac{3}{32K}](m_H)(V_g^2) \sin^2(\theta_i + \theta_s)(\frac{\theta}{\theta_s})^{4/7} , \quad (6b)$$

Galactic Motion as Sources for Heating of the Intergalactic and Intracluster Medium

by

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ABSTRACT

It is often suggested that the motions of galaxies can play a role in the heating of the intergalactic or intracluster medium. In the specific case of the Coma cluster it is shown that under ordinary assumptions the motion of its galaxies probably could not have heated the hot gas there. Under certain conditions of galactic structure and cluster evolution, however, significant heating from the motions of galaxies would be expected. Evidence is also presented indicating that the two giant ellipticals near the center of Coma may be able to provide most of the drag heating required by x-ray observations. The effect of galactic motions on a possible clumpiness in the intracluster medium is also discussed for Coma. Finally the possibility that galactic shocks played an important role in the heating of the general field IGM is discussed briefly and dismissed.

Recently several authors have discussed the possibility that the intergalactic gas is heated by the supersonic motions of the galaxies. Earlier reviews of the thermal history of this gas (Ginzburg and Ozernoy, 1966, Weymann, 1967) as well as the most recent reviews of the subject (Field, 1972) speculate on various kinds of heat sources. More specifically, certain authors have dealt with the various aspects of shocks from moving galaxies and galactic wakes (Spiegel, 1970, Rudermann and Spiegel, 1971, Hunt and Sciama, 1972). We would like to re-examine the possible effects of galactic shocks on the intergalactic gas both in clusters and in the general field.

Review of Shock Mechanism

In the Rudermann and Spiegel model (Hereafter referred to as RS) the details of a wake shock from a supersonic galaxy are worked out, and arguments are provided to motivate the bow shock as well (see our Figure). RS argue that the presence of the bow shock depends on whether or not the galaxy itself has enough internal pressure or magnetic field to support a shock. Hunt (1971) takes the position, however, that the bow accretion itself supports the gas through pressure gradients that build up as the gas falls into the galaxy.

The RS model is characterized by an x-ray luminosity:

$$Q_0 \simeq 4 \times 10^{28}\ \Omega^2\ R_g^3\ V_g (R_a/R_g)^{\frac{1}{2}} \text{ergs/sec} \ , \qquad (1)$$

where Q_0 is the free-free output of a single galaxy where m_H is the mass of an H atom. This is much less than the observed values (close to 10^8 deg. K) for the galactic sizes and velocities considered here. For these values we see that the wake shock heats and compresses only a relatively small amount of gas in a region far behind the galaxy. From the RS calculations the shock temperature for cold background gas would be much less that the required temperature of 10^8 degrees, but as RS point out, their results hold only for cold incoming gas. The notion of radius of accretion, however, is a general one which measures the effectiveness of the gravitational interaction between moving objects and the background medium; and the small size of the radius of accretion here leads to the conclusion that no model of gravitational wakes will produce the heating required in Coma. Taking into account results for bow shocks, we can state that galactic motion seems unable to heat the gas in the Coma Cluster to the required temperatures.

However, some recent speculative suggestions may change this conclusion. As we shall shortly demonstrate, any galactic gas present initially in the galaxies in Coma would be swept out under most conditions into the intracluster medium by the ram-pressure of the background gas. Furthermore, gas is continually produced, even in gasless ellipticals, by the ordinary processes of stellar evolution and decay: Yahil and Ostriker (1973) estimate that on the average as much as 1 $M_\odot$/yr per galaxy may be freed in this manner. In our model the initial intracluster gas in Coma is first heated by shocks over the discs of ellipticals when they still contained gas. This galactic gas, however, is swept away in a time small compared to the age of the cluster, and this gas, originally traveling with the known random velocity of its parent galaxy ($\sim 1.7 \times 10^8$ cm/sec) thermalizes with the cooler background gas. In the final stage accretion shocks are only of minor importance, but the galaxies in the center continue to shed gas, as stellar decay products, which is swept out.

The initial drag from galaxies which had gas, and thus could support ram-type shocks over their entire cross section, is given by $D_g \sim \rho_b V_g^3 \sigma_g$. However, as long as the temperature T in the interstellar gas is such that its pressure, given from the gas law as $n_H KT$, (n_H the interstellar particle density) is less than the ram pressure of intergalactic hydrogen, $\rho_b V_g^2$, then ram pressure could overcome the gas pressure in the galaxy.

However we must ask whether the galactic gas would fall out of a speeding galaxy under these conditions. Looking at a galactic disc moving through the ambient medium we see that the ram pressure force must also overcome a gravitational force from the stars of $g\sigma$, where g is a kind of average gravitational acceleration due to gas and stars in the galaxy , and σ is the column density of material in the disc. Ram pressure tries to push the gas away from the stars. If the ram pressure cannot initially overcome this restoring force then the galaxy will forever sweep up gas, as accreted gas further increases the values of σ and g.[1] The kinetic energy of mass motion of that gas initially in galaxies will, in the case of clean sweeping, then be shared with the ambient gas, and the lack of spirals in

1. I am grateful to an anonymous referee for suggesting this argument.

Coma suggests that a process similar to this one acted to sweep the ellipticals of their gas, though in any case the original galactic gas densities were probably high enough in the galactic nuclei to allow gas to accrete there.

Because of the relatively high speeds of galaxies in Coma (V_g = 1.7 x 10^3 km/sec) most galaxies which will ever have passed through the center of Coma will do so within 10^{10} years. Of the 1200-1300 objects in the Abell data (after background corrections) in an area of 7 square degrees, most have an actual crossing time of about 5 x 10^{16} h^{-1} sec. (the square has the same area as a circle of 90 minutes in radius). Each of these galaxies which does in fact impinge on the central part of Coma loses energy and sheds gas, thus heating up the core.

The total energy thus released can be calculated from knowing the mass shed and the speed at which the mass was originally moving. Allowing a typical initial average galactic gas density (hydrogen) of about 1 particle/cm and a density of the original IGM of about 10^{-3} particles/cc, with 1000 galaxies contributing 10^{70} particles (about the number initially there), we find a total of about 2 x 10^{62} ergs added to the IGM in Coma. This amount of energy averaged over the present volume and density of the IGM corresponds to a particle temperature of 5 x $10^{7\circ}$ K, close to the value expected from observations of x-ray emission (Gursky, et al. 1972). In addition a further input from the stellar decay products (the Yahil-Ostriker mechanism) of about 5×10^{25} gm/sec per galaxy per second from 50 galaxies actually in the center at any one time, produces an additional continuous

$$50 \times (\frac{1}{2} V_g^2 M_\odot) \text{ ergs/yr } \underline{\text{or}} \text{ } 5 \times 10^{43} \text{ ergs/sec} \qquad (8)$$

of kinetic energy which replaces somewhat the radiation losses of the plasma. Since the cooling time at this temperature is longer than the age of Coma, the combined effects of the sweeping out of the original gas and the shedding of remnant gas provide the energy to maintain for some time the x-ray emission seen today. Actually this is an underestimate since if there is much less gas in the rest of Coma than in the center, galaxies will accumulate mass during most of their lives from stellar decay and thus lose more only when they pass through the center of Coma.

If on the otherhand we revise our estimates of galactic mass-to-light ratios up in order to "bind" the Coma cluster with the available luminous objects, then the relevant drag associated with shocks and wakes goes up by almost two orders of magnitude. Recalculating the radius of accretion, Eq.(3), using a galactic mass of 10×10^{11} $M_\odot$, we find the drag cross section to be about 50 times greater than before and the total drag from 50 galaxies in the Coma core about 10^{44} ergs/sec. Actually the drag rate must be multiplied by a factor $1/[1 + (V_g^2/C_\infty^2)]$ to account for the fact that the speed of sound is near the speed of the galaxies (i.e., low Mach number) and the radius of accretion is slightly reduced. Still, 50 sources of this strength will heat the background gas until the temperature is about 10^8 °K, where the free-free cooling rate equals the input heating.

Thus galactic shocks, in the cluster case will produce significant inputs to the intergalactic medium heat balance only under certain hypotheses about galactic structure and evolution, or under certain histories for the evolution of clusters themselves. Galactic shocks alone, as suggested by Ruderman and Spiegel, or Hunt, will not, under ordinary circumstances, have any important effects, though as these authors point out, certain x-ray observations may be explained by the galactic shock mechanism. Moreover most galaxies in Abell's sample have masses of less than $10^{11}M_\odot$, and so our estimates of total energy released are really upper limits. It should be pointed out, here, that decreases in the value of the Hubble constant (seen through the parameter h in our calculations) cause the total intrinsic luminosity of Coma to change by a factor h^{-2}, while the volume changes by (h^{-3}). The radiation seen would then by coming from a thinner plasma occupying a larger volume, containing, however, the same number of galaxies; thus the drag heating mechanism would be less efficient because of the decrease in the background particle density, which scales here as h from x-ray observation. If new observations lowered the observed temperature, however, the resulting energy output would also decrease, favoring the shock mechanism.

One additional possibility for improving the shock mechanism in Coma comes from considering the two brightest galaxies in Coma, NGC 4874 and NGC 4889. These galaxies (call them G_1 and G_2) have radial velocities relative to Coma of - 207 (V_1) and + 418 (V_2) Km/sec (Rood, et al. 1972) and photovisual magnitudes of 12.3 (pv_1) 11.6 (pv_2) . (Abell, 1974). The objects are found spaced nearly equidistant on opposite sides of the center of Coma, with $D_1 = 3{\cdot}2'$ and $D_2 = 4'$: (1 minute of arc = 26.75 h^{-1} K pc). We should examine the consequences of the hypothesis that these objects are circling about each other (and the Coma center) so that their radial velocities are nearly their <u>real</u> velocities. Using the relationship between Luminosity (L), Mass (M), and photo-visual magnitude (pv), we have

$$M_i = f\ L_i = (f)(10^{-.4(pv_i\ -\ 34.8\ -\ pv_\odot)})h^{-2\,*} \qquad (9)$$

where f is the mass to light ratio, and $pv_\odot$ is the absolute photo visual magnitude of the sun, 4.8 , and i = 1 or 2. Using f = 30 (though this much discussed figure may be quite higher) (Peebles, 1974, private comm.; Rood, 1964) we find for G_1 and G_2 .

$$\begin{aligned} M_1 &= 2.5 \cdot 10^{12}\ h^{-2} M_\odot \\ M_2 &= 4.8 \cdot 10^{12}\ h^{-2} M_\odot \end{aligned} \qquad (10)$$

These values correspond roughly to those needed to hold the two galaxies in orbits around each other, as estimated by comparing the gravitational and centripetal accelerations. But we can re-write Eq.3a to find the drag associated with these objects. For a background

*The distance modulus of Coma for h = 1, a distance of 92 mpc, is 34.8.

density parameter $\Omega = 700$,

$$D_i \sim (.6)\left(\frac{M_i}{10^{11}M_\odot}\right)^2 \left(\frac{V_i}{100\ \mathrm{km/sec}}\right)^{-1} h^{-1} \qquad (11)$$

in units of 10^{42} ergs/sec. If $V_i \gtrsim$ speed of sound, C_∞, D_i must be multiplied by $1/(1 + V_i^2/C_\infty^2)$; for G_1 and G_2 the observed speeds are much less than the observed gas sound speeds (Margon, 1973) and so the accretion mechanism for drag heating is most effective: The heating is supplied by Hunt's mechanism, as incoming gas is compressed. The calculated drags are

$$D_1 \sim 1.9 \cdot 10^{44} \text{ ergs/sec}$$
$$D_2 \sim 3.5 \cdot 10^{44} \text{ ergs/sec}, \qquad (12)$$

significantly greater then that provided by all the faster moving, lighter galaxies. If the Mass-to-Light ratio of galaxies in Coma were high enough to bind that cluster, ie; 200 (Rood et al. 1972) then the output from drag heating by these two galaxies as well as all other galaxies would be truly enormous.

Furthermore unpublished work in progress by the author shows that the distribution of luminous galactic matter is more peaked towards the center than previously thought (see Rood et al. 1972) and thus Ω >700 (for the central volume occupied by G_1 and G_2.) under the assumption that the intergalactic gas in Coma is distributed similar to the mass of Coma.

Clouds in the Coma Cluster

It should also be pointed out that galactic motions in clusters would influence greatly the stability of clouds of cooler gas suggested by Silk (1970) and Goldsmith and Silk (1972, referred to as GS). These authors postulated a cluster clumpiness parameter

$$C = \frac{\langle n_b^2 \rangle}{\langle n_b \rangle^2} \qquad (13)$$

where n_b is the particle density of H over the whole cluster. Alternatively, "C" is the fraction of volume of Coma actually occupied by gas if the gas is in clouds, and $\langle n_b^2 \rangle$ is the average of the square of the density. GS evaluate the possible values of C from the observed properties of Coma, to see if enough gas would be in the form of cooler clouds to bind that cluster. They found that the most likely value of C is 100, that the typical cloud has radius of 120 kpc, density $C\, n_b \cong 10^{-1}$/cc and internal temperature less that $10^{5\circ}$ K. The cloud as a whole is moving about the center of the cluster with the RMS speed of the galaxies, 1700 km/sec, so that clouds will not fall to the center. The limits on C also take into account the condition that cloud-cloud collisions are unlikely, and that relaxation of the cloud-galaxy system would not evaporate away the galaxies in a short time compared to the age of Coma. However, they fail to account for galaxy-cloud collisions, which occur with frequency

$$\nu_c = n_{gal}\, \pi R_c^2 V_{coll} = (13 \cdot 10^{12} c^2 \text{ sec})^{-1} \qquad (14)$$

where $n_{gal} = 3 \times 10^{-72}$ galaxies/cc is the density of galaxies in the center of Coma from unpublished calculations which the author has made on Abell's data, including galaxies down to m_{pv} of 18.

The total energy released is $D_A t^*$, with D_A given by Eq.(3):

$$8.5 \times 10^{59} \left(\frac{V_{coll}}{10^7}\right)^{-2} \text{ ergs} \tag{15}$$

which even for $V_{coll} = 2.5 \times 10^8$ could disrupt the equilibrium of the cloud. Certainly the recent x-ray observations of Coma rule out the possibility of cool clouds in the dense, hot center. The above considerations of dynamics of galactic motions probably rule out the presence of large clouds in the rest of Coma, too.

*A collision lasts a time $t = R_c/V_{coll}$.

Galactic Shocks in the General Field

In the general field galactic wakes and shocks were suggested as possible important sources for the general heating of the IGM (RS, Weymann, 1967). However detailed calculations, using the techniques of Field and Henry (1964) for integrating back to arbitrary values of z, the red shift, show results quite insignificant, in contrast to suggestions in RS. RS in fact claim that the ouppt from a single shock would depend on a high power of z, $(1 + z)^{13/2}$, while our calculations show a 5/2 or 7/2 power dependence. This difference is due to the use of comoving coordinates as outlined in Field and Henry 1964, and part of the confusion arises from the fact that at higher speeds the galactic wake shocks become less effective, since the relevant parameter δ scales inversely as the square of the galactic speed, with respect to the background gas, which in many cosmological models increases in the past. (Peebles, 1971) Furthermore the bow accretion shock treated in Hunt (1971) also becomes less effective in the past as the radius of accretion cross section also decreases, while the Mach number remains constant or increases.*

Using parameters suggested by RS one finds an x-ray intensity today one or two orders of magnitude below that which is observed, even taking into account the most favorable cosmological conditions and indeed the speculative heavier galaxy models of Ostriker.

*Taking the Mach number as the ratio V_g/C_∞ we are reminded that both these speeds increase in the past with most cosmological models, though "reheating" models for the IGM would give even greater Mach numbers in the past.

Furthermore the actual fraction of the whole universe shocked, which can be calculated from the RS models for a variety of drag cross sections is $\ll 1$: the drag process cannot have affected much of space. Finally one can consider each galaxy as a heat source of strength ρ per unit volume of space and integrate back in time, following the field galaxies as they speed up and move closer in space and noting the various cooling processes available to the IGM (Ginzburg and Ozernoy, 1966). Again the heating cannot keep pace with either free-free cooling or the adiabatic cooling from the expansion. Furthermore the radiation from all shocks is not enough to even maintain ionization of the IGM at a lower temperature, a process suggested by Rees and Setti (1969) and Bergeron and Salpeter (1970) in connection with quasars and background UV radiation.

Therefore we must conclude that while galactic shocks and drag heating could, under certain conditions, play an important role in the temperature and heat balance in clusters like Coma it is doubtful whether such mechanisms would ever show any importance on a large, global scale.

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FIGURE CAPTION

Fig. 1 Galaxy and Associated Shocks. Bow shock and wake (B and W) when $\delta \equiv (2GM_G)/(V_G^2 R_g) \sim 1$ and when $\delta \sim 1/6$ (B' and W'). For a galaxy of Mass $\sim 10^{11}$ $M_\odot$ with a speed typical of that observed in Coma $\delta \ll 1$, the wake, if any, would be off the scale to the right. The galaxy is moving to the left.

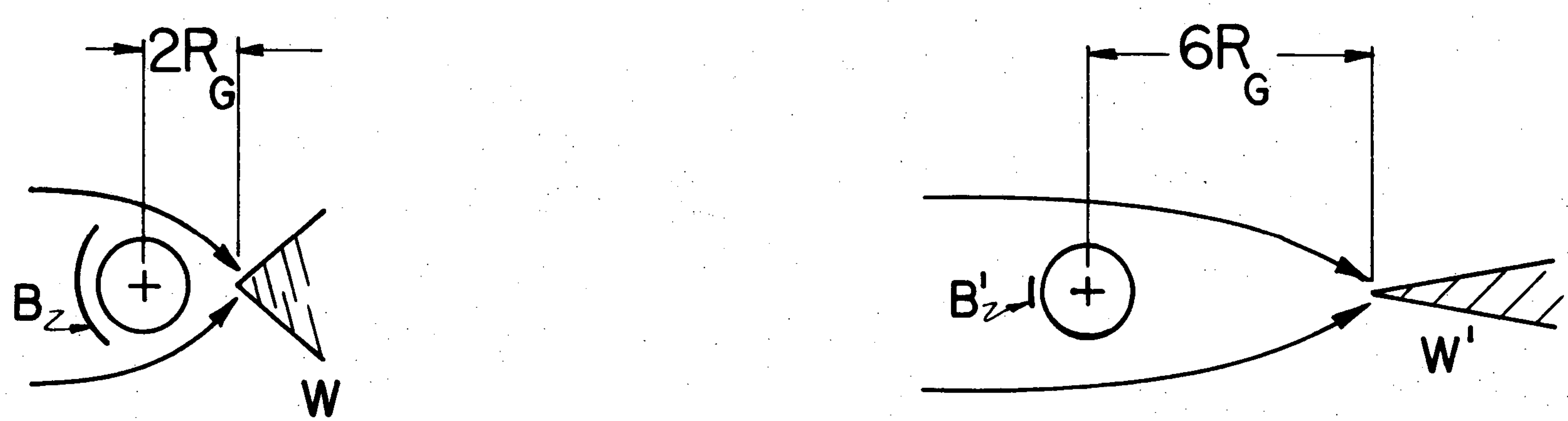

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Fig. 1.

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