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THE VIOLENT INTERSTELLAR MEDIUM

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HIGH VELOCITY GAS IN THE GALACTIC HALO AND DISK

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The progress in the understanding of the high velocity component of the interstellar medium is reviewed. Emphasis is on the velocities seen outside the plane of the Milky Way, of gas in the galactic halo.

The extensive measurements of interstellar absorption lines in the late 1930's demonstrated that the "stationary" lines in stellar spectra were extremely narrow and in many cases showed fine structure at the 10 km/s level. The quantisation of these data had to wait until about 1950. Adams (1949) presented data on Ca II lines toward some 300 stars and his compilation, supplemented with Na I data, led Routly and Spitzer (1952) to investigate the systematics of the Ca and Na abundances. Contrary to the non-solar abundance ratio of the majority of the interstellar clouds, the "high velocity" absorptions, defined by Routly and Spitzer as differing in velocity by more than 20 km/s from the local standard of rest, showed a near solar Ca/Na abundance ratio.

Around that time it became clear as well that most of the velocities seen were due to the effects of galactic rotation (Spitzer 1948, Spitzer and Oke 1952). With observing techniques improving, Guido Münch (1957) looked at interstellar absorption lines in distant stars and he convincingly showed that velocity and galactic longitude of the clouds correlate very well. His figure became a classic of astronomy, not only showing galactic rotation, but also revealing the presence of distinct spiral arms. In a related study, Blaauw (1952) found that the interstellar absorbing clouds in the solar neighborhood had a dispersion in velocity of about 5 km/s. Thus most velocities could be understood as due to gas moving orderly in a rotating galaxy, with a few odd high velocity clouds speeding through some intercloud medium.

With the availability of detectors for the 21-cm hydrogen emission, galactic rotation was further probed. Distances of gas were derived from a model for the galactic rotation. This led to another classic figure, the spiral pattern of our Milky Way (Oort 1962). Personally I had some problems seeing "spirals" in the structure. Due to the

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necessity to use a model for the rotation of the Milky Way, any peculiar velocity present is forced, of course, into representing some distance, and so the true spiral arm pattern of H I gas is blurred. That our galaxy has decent spiral arms may follow from the analogy with galaxies such as M81 and M101 where spatial interferometric 21-cm maps show clear cut H I gas spiral arms. Very much later, when the galaxy was surveyed in CO radio-line emission, Burton and Gordon (1978) made CO-model maps and showed that a good fit to the observations is obtained with a model where the CO clouds have a stochastic spatial distribution and a cloud-cloud velocity dispersion of about 4 km/s. This dispersion is remarkably close to Blaauw's absorption cloud value. Thus, because the velocity spread of the CO maps is hardly different from the velocity spread in the H I 21-cm maps, one might infer that the H I gas has velocities consisting of galactic rotation with only some minor spread superimposed.

Special effort is required to study gas outside the Milky Way disk since "early type star with large z" is a "contradictio in terminis". Münch and Zirin (1961) presented data for 24 stars with z up to 2 kpc and discussed the clouds detected. Again the Ca/Na abundance anomaly was found. But no explanation for the prepondarance of the "high velocities" at large z was available. Based in part on early reports of the large z data, Spitzer (1956) had proposed the existence of the gaseous galactic corona as a means to hold the high z clouds together.

Further understanding of absorbing clouds and their velocities came with the availability of ultraviolet spectrometers. Measurements with the Copernicus and with the International Ultraviolet Explorer (IUE) gave access to many other atomic resonance lines. In particular the lines of Mg II and of C II, with large optical depths mainly due to the large intrinsic elemental abundances, showed to be very sensitive probes of interstellar gas. Actually, with the currently available IUE, the UV-resonance lines are about an order of magnitude more sensitive than the 21-cm emission, in detecting low column density clouds (see e.g. Savage and de Boer 1981). Therefore it is not surprising that also on those lines of sight, up to then well studied in the visual, additional absorption components were detected. This in all cases meant an increase in the range of velocities over which interstellar absorption was seen. In particular toward the hotter stars the absorption due to C III and Si III was detected over large velocity ranges, mostly more negative than the velocities for lower ionization stages on the same line of sight (see Cohn and York 1977).

Completely independent of this were the studies of emission line nebulae. Already in 1918, radial velocities were measured for planetary nebulae, including line splitting (see Dufay 1957). They were well understood as due to expanding shells of gas around the central stars. Quite less clear was the case for the diffuse emission nebulae, although a larger intrinsic width of their emission lines had been noted. Neither a clear velocity correlation seemed to exist with the velocities of the illuminating stars, nor did they show "high velocities". The use

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of spectral interferometric techniques has expanded our data base a great deal. Work done on galactic H II regions (see e.g. Meaburn 1977; Hippelein and Münch 1981) shows the potentials of understanding emission nebulae by also measuring accurate velocities. H-alpha emission from the diffuse gas was studied extensively first by the group at Marseille (see Georgelin and Georgelin 1976), and later by Reynolds (1980).

Three great nebulae have been studied in the visual and the ultraviolet in detail. In Orion absorption velocities are between -40 and 0 km/s for the line centers, or between -100 and +30 km/s for the edges in the C II line (Franco and Savage 1982). Reynolds (1980), measuring the diffuse H-alpha emission, found radial velocities ranging over 100 km/s in the related Eridanus region. In the Vela supernova-remnant (Jenkins et al 1981 and refs.) velocities are found to range between -180 and +90 km/s. In Carina (Walborn and Hesser 1982; Laurent, Paul and Pettini 1982) the velocity ranges even between -350 and +200 km/s. Such large velocities must have to do with very energetic events. In contrast, many isolated O stars have H II shells with so little expansion that for the entire emission a turbulent velocity of only about 6 km/s is indicated (Reynolds and Ogden 1982). And, comparing CO emission with H-alpha emission from H II complexes, Fich, Treffers and Blitz (1982) find an average velocity difference between neutral and ionized gas of only 1.5 km/s (with a dispersion of 4.5 km/s), suggesting very little expansion indeed. High velocity gas is a well established aspect of stellar activity. Stellar winds, strong radiation fields, and supernova explosions will induce the formation of ionized cavities around early type stars and clusters (for theory see Weaver et al 1977, and refs). The range of velocities found seems to correlate with the energy of the star or stellar association. Thus, on an overall galactic scale, high velocities due to H II regions may be ragarded as very notable, yet local disturbances.

Is there any high velocity gas outside the regions directly influenced by stars? The largest velocities found by Münch and Zirin toward high z stars are about 60 km/s off the LSR, still pertaining to gas within 2 kpc from the galactic plane. Gas supposedly outside the galactic disk was also found using the 21-cm H I emission line. The measurements are scattered, but a review is available from Hulsbosch (1979). Most of these H I clouds show negative velocities which led to speculations on infalling intergalactic material. But there was a bias due to northern hemisphere data, as has become clear from the high velocity cloud survey of Giovanelli (1980). Working with an overall detection limit of a little better than 10(+19) cm(-2), some 750 high velocity emissions were found in the total of 6000 profiles. Due to confusion by the Milky Way disk, the detections effectively are only for radial velocities differing by more than 50 km/s from LSR. Giovanelli's figure 5 represents all the data. Two features are noteworthy. First, clouds detected at velocities more negative than -200 km/s are found between galactic longitudes 40 and 200 only; these can be understood as gas in the Magellanic Stream (Mathewson, Cleary and Murray 1975). The other feature is the (observational) scarcity of southern hemisphere

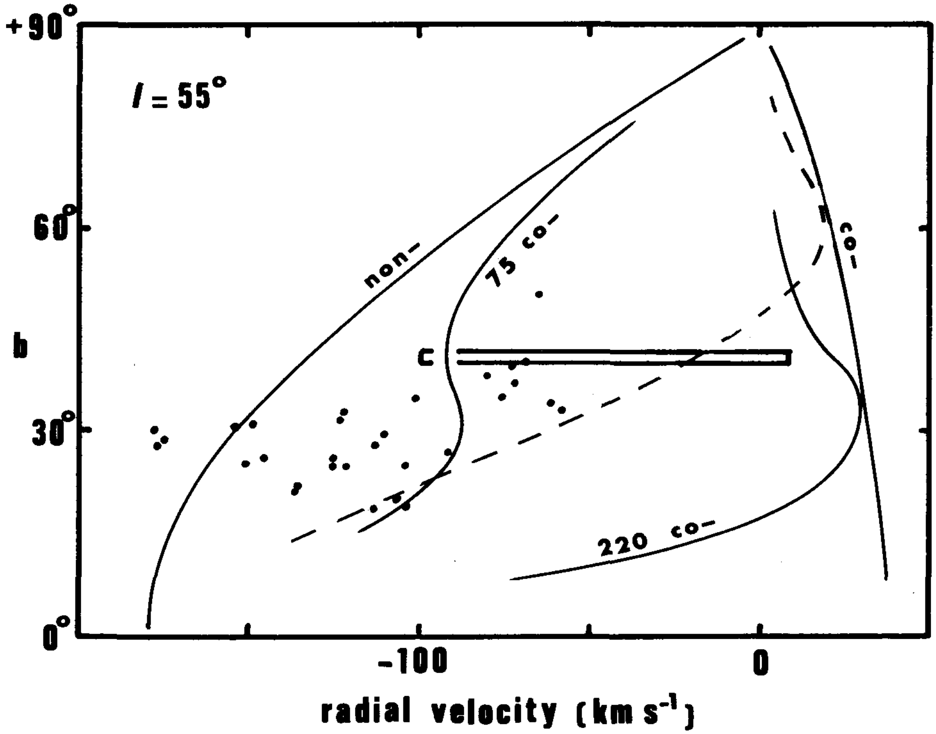

Figure 1. Radial velocities as would be expected from different types of rotational behaviour of galactic halo gas are plotted versus galactic latitude for a given longitude. The curve labeled "non-" is for a halo not rotating at all; the velocities are a true reflection of the motion of the LSR. The curves "220 co-" and "75 co-" give velocities expected from gas at z= 3kpc which rotates (as a cylinder) along with the disk at a speed of 220 km/s (as the LSR does) or with 75 km/s. The unlabelled dashed curve is for gas at z= 10kpc with cylindrical rotation of 220 km/s. The curve labeled "co-" gives the positive velocity limit for gas at any z with rotational speed of 220 km/s (actually at the tangential point).

The points in the figure represent clouds detected by Giovanelli (1980) in the longitude range of 50°-60°. The absence of points toward 0 km/s as well as at latitudes below 15° is due to selection effects. From this diagram it follows that the clouds behave intermediate to the following two extremes (see de Boer and Savage 1982); a) the halo corotates at 220 km/s and the clouds are at large z; b) the halo clouds are at small z and hardly participate in the galactic rotation. The trend present here can also be seen in plots for the adjacent longitude regions.

The bar shows over which velocity range absorption was detected with the IUE toward the globular cluster M13, which is in the direction l=59° and b=41° at z= 4kpc (de Boer and Savage 1982). Those data are consistent with a smaller rotational speed of the gas at larger z distance.

data. One could supplement Giovanelli's figure with the high velocity clouds (HVC's) detected in the UV with IUE at +60 and +120 km/s in the direction of all stars of the Large Magellanic Cloud studied thusfar (Savage and de Boer 1981). These clouds actually have just recently been detected in H I 21-cm at Parkes (Donald C. Morton, priv. comm.). Considerable effort has gone also into extending the Ca data base of Münch and Zirin, by Blades (1981), and by Songaila (1981), and York et al (1982), using Magellanic Cloud stars and extragalactic objects as background light sources, but only few Ca HVC's were found. The whole collection of HVC data shows a sinusoidal distribution of data points in the longitide velocity plot, which go right along with what would be expected from galactic rotation. Hence one might be tempted to say that this high velocity phenomenon is just due to a quietly rotating galaxy, leaving no room for real deviant velocities.

When Giovanelli's data are replotted in velocity-latitude coordinates, it is found that for a given (small) range in longitude the data fall along a strip which has velocities consistent with a Milky Way halo rotating modestly along with the plane (see figure 1.). A severe limitation in the further interpretation is that for all data points the distance is unknown. Observations with IUE of a bright blue star in the globular cluster M13 (de Boer and Savage 1982), which is at a z distance of about 4 kpc, also showed (negative) velocities as expected from galactic rotation. However, the limit on the distance of the cluster makes the observed velocities "forbidden". Since this is the only information available on gas out to a known 4 kpc (of the Münch and Zirin stars only one was as far as 2 kpc) it may be to early to make any definite statement on the rotational behaviour of gas in the Milky Way halo. With the M13 data, de Boer and Savage were tempted to speculate on a possibly exponential decrease in the rotational velocities when reaching to larger z. Also, we must bear in mind that these results pertain to cool gas only (the UV detections mainly refer to C II, Fe II type species), gas which may have a kinematic behavior different from that of other types of gas.

Hot gas (T=10(+5)K, the temperature from assumed collisional ionization) has been detected away from the galactic plane with the IUE in the resonance lines of C IV and Si IV. Pettini and West (1982) measured the C IV and Si IV lines to 24 high galactic latitude stars and recognized that little, if any, C IV gas is present nearer than 1 kpc from the galactic plane. Including the M13 data, de Boer and Savage arrived at a scale height of C IV gas approaching 4 kpc. The velocities associated with hotter gas come from the same absorption lines. The spectra toward Magellanic Cloud stars show C IV absorption extending up to +130 km/s (Savage and de Boer), with strongest absorption between 0 and +30 km/s (in accord with no C IV within 1 kpc). Only for a few lines of sight to high z stars uncertain velocities are available. Towards M13 de Boer and Savage were able to recognize high ion absorption between -100 and 0 km/s, over almost the same velocity range as the C II absorption. The absorption on the Magellanic Cloud lines of sight did not show velocity structure like the low ion lines and it was concluded that the gas, if in "clouds", had temperatures of over 10(+5) K, or was smooth in velocity and hence in spatial distribution. The overall structure of Milky Way gas (see Cox 1981) with cool clouds in a hot matrix likely supports an extended external region of hot gas fed by the galactic wind. With a mass flux in the fountain of the order of 5-10M⊙/yr (Cox) and initial pressure balance at nT= 2000 K/cm(+3), the outflow velocity is larger than 100 km/s. These velocities occur in the hot matrix-type gas at 10(+6) K, hence having ions not available for detection with current techniques.

The original Milky Way corona model of Spitzer (1956) was expanded upon by Shapiro and Field (1976), who introduced the idea of a galactic fountain. The subsequent models by Bregman (1980), in which a cooling condensation in its orbit outside the galactic plane is followed, reproduced (at large) the velocity distribution of HVC's over the sky. The models also predicted an excess galactocentric motion of the cool HVC's. Inspection of Giovanelli's figures shows that the slight shift of the nodes in the longitude-velocity plot indeed can be best understood as due to a galactocentric velocity component (de Boer and Savage).

Summarizing, the motions of gas in the disk of a galaxy essentially are smooth, as also inferred from external galaxies. The environment of hot stars may, of young associations will always, show high velocity interstellar gas. The motions are due to expanding shells or shocks, and will be mostly at a velocity negative w.r.t the ambient medium when seen in absorption. In a sense, such gas represents the only true high velocity gas. The Milky Way likely possess a galactic wind type outflow into the galactic corona. Condensations in the flow will cool and descend. The observational evidence suggests that gas in the corona participates probably to only a limited amount in the rotation of the Milky Way at large. Velocities of gas seen toward high galactic latitudes will therefore largely reflect the rotation of the LSR.

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