THE MILKY WAY: A HALO, A CORONA, OR BOTH?

Klaas S. de Boer
Astronomisches Institut Tubingen, D-7400 Tübingen,F.R.Germany

The detection in absorption lines of gas clouds outside the galactic plane at high velocities by Münch and Zirin (1961), high velocities then defined as velocities differing by more than 20 km/s from the LSR, showed that the space outside the Milky-Way disk contains not just stars. Of course, from a continuity argument it had been all along clear that some transition zone had to exist between the dense (relatively speaking) gas of the Milky-Way plane and the vast (almost) emptiness of intergalactic space. The presence of these clouds requires a mechanism to prevent their evaporation, and Spitzer (1956) proposed that dilute hot gas had to exist outside the Milky-Way disk reaching, in his hydrostatic-equilibrium model, temperatures of a few million K at several tens of kpc. These high temperatures led him to name these gases the Galactic Corona. Observational confirmation of the abundance of these cool clouds came from the measurements of 21-cm HI emission, but no one-to-one correspondence with clouds detected in the visual did appear (Habing 1969). For the majority of the high-velocity (HV) clouds (Hulsbosch 1978) no distances are known, and all of those are believed to exist as a gaseous halo with the halo stars. Thus our Milky Way appears to have outside the disk: a halo, a gaseous halo, and a corona.

The nomenclature in the studies of the distant material is getting confused. In studying the gas, the location aspect has been emphasized using the word halo, the (high-temperature) gas aspect by using the word corona (De Boer and Savage 1982). In cosmic-ray and gamma-ray studies (Ginzburg 1978; Stecher 1978) also the spatial aspect is emphasized with the word halo. For models of the dynamics of the Milky Way the nuclear bulge, disk and halo are well-known entities. Einasto (1978 and references given there) demonstrated the need from dynamics for a large and very extended spheroidal mass, which he called corona. Later papers (Caldwell and Ostriker 1981; Rohlfs and Kreitschmann 1981; etc.) used the word corona as well. There is, however, an etymological objection against the use of the word corona in this case, since this hypothetical component is neither brilliant, nor always taken spherical. MASsive DArk Component (MASDAC) is more descriptive and is not in conflict with the older use of the word corona for hotter gases such as

H. van Woerden et al. (eds.), The Milky Way Galaxy, 415–420.

stellar corona, galactic corona (Spitzer 1956) and (less appropriate) the geocorona (Wegener 1911).

Cool gas in the Milky-Way halo has been detected on many lines of sight, using galactic as well as extragalactic background light sources. The original CaII-line studies of Münch and Zirin were extended by Blades (1981), and by Songaila and York (1980), but UV large-optical-depth absorption lines (e.g. CII, SiII, MgII and FeII) are very good probes for clouds in the halo (Savage and De Boer 1979, 1981 = SdB81; Pettini and West 1982; York et al. 1982; De Boer and Savage 1983 = dBS83). I want to stress that the CII lines seen in extragalactic sources show saturated absorption over wide velocity ranges, so there is "neutral" gas along vast portions of sightlines. Abundances are near solar (SdB81).

Distances of HV clouds are hardly known. Using galactic background light sources, one has a limit on the distance of the absorbing gas. Lines of sight to stars at z larger than 1 kpc and having HV clouds are rare: Münch and Zirin found 2, Pettini and West added 1, Songaila and York possibly 1 (M15), all with velocities differing less than 30 km/s from the LSR, and dBS83 found absorption at up to -100 km/s toward M13 ($z=4.1$ kpc). To extragalactic sources essentially always absorption by low-ionization-state material was detected in the Milky-Way halo (see York 1982 and dBS83 for references). This, in connection with the paucity of detections using galactic (so relatively nearby) background sources, I think means that many HV clouds exist at distances beyond 2 kpc.

Velocities are easy to measure in absorption lines. Insofar as the detections are toward high-latitude objects, the information supplements the 21-cm HV-cloud survey data of Giovanelli (1980). In particular, UV data from LMC and SMC stars extend the evident sinusoidal distribution of data points in a (l,v) plot into directions not extensively searched. Note that the HV clouds seen toward LMC and SMC stars now have been detected at 21 cm by McGee, Newton and Morton (1983). The large forbidden negative velocity found toward M13 led dBS83 to emphasize that the halo very likely rotates at lesser speed than the disk. This also would be more in line with dynamical models (Feitzinger and Kreitschmann 1982). An extended gas disk ("halo") as found by Lockman (1983) is compatible with e.g. an exponential decrease of velocity with height outside the first 1 kpc, with a scale height of perhaps 4 kpc. The limiting cases have been discussed recently by De Boer (1982).

Hot gas outside the disk shows its presence in the CIV absorption lines. The first detection, together with simple halo corotation, suggested an extent of CIV gas of up to $z = 10$ kpc (Savage and De Boer 1979). With the evidence for lesser rotational speed, the extent of the CIV gas as derived from velocities may be just a few kpc (dBS83). The scale height of CIV gas can be derived from plots of latitude-corrected CIV column densities versus z. There is no doubt that there is little, if any, CIV gas within 1 kpc from the Milky-Way disk (SdB81; Pettini

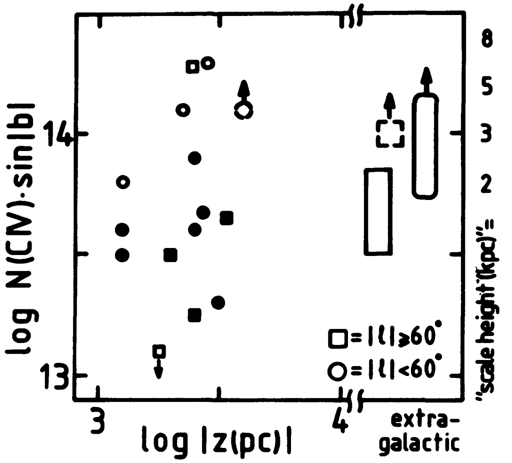

Figure 1. All CIV column densities toward high – latitude objects available in the literature are (latitude – corrected) plotted versus distance away from the Milky Way plane. The data are sorted twofold: filled symbols represent "accurate" data while open symbols the less secure determinations; the shape of the symbols refers to the general galactic directions of the light sources. Data for log z < 3.55 are from Pettini and West (1982). The entry at 3.6 is for M13 from dBS83, the tall box represents the range from the LMC star data (SdB81; Gondhalekar et al 1980), the rounded box the SMC star data (SdB81; Prevot et al 1980), and the small box 3C273 data (Ulrich et al 1980). Both SdB81 and Pettini and West have only upper limits below 1 kpc. The scale height of the CIV gas may be a few kpc. The entries for the "outer" longitudes of the Milky Way seem to suggest a smaller scale height than those for the "inner" directions.

and West 1982). Figure 1 shows that the scale height may be a few kpc. I think there is some indication that the scale height of the CIV gas is larger inside the solar circle than in more outward directions. If true indeed, this may have to do with larger star-formation and supernova rates in the Milky Way between R = 5 and 8 kpc.

The density of the gas seen in the halo can be roughly determined. The column densities (to LMC stars) in 21-cm gas and in CIV gas both are about $N(H)=10^{19}$ cm^{-2}. The clouds detected in front of the LMC appear in all UV spectra recorded, over 3° of the sky (SdB81). If such a cloud were at $z = 2$ kpc, its radial extent would be 100 pc. At 2 kpc the gas pressure is perhaps a factor 2 less than in the disk, at about 10^4 $K.cm^{-3}$. The HI cloud may be at 10^3 to 10^4 K, thus indicating a density of 10 to 1 cm^{-3}, and so a thickness of 0.3 to 3 pc. From the CIV absorption profile, as well as from the total column density, it followed (SdB81) that on the LMC line of sight $n(CIV)=10^{-8}$ cm^{-3} at a (revised, smaller) z of about 4 kpc. The lower limit to the gas density so becomes (solar abundance, all C in CIV) $n(H)=2\times10^{-5}$ cm^{-3}. Abundances are near normal on these lines of sight (SdB81; McGee, Newton and Morton 1983), but the ion fraction may be small (10% at most for collisional ionization), and so n(H) may be even 10^{-3} cm^{-3}. On the other hand, if indeed the CIV gas is at 10^5 K (Hartquist and Tallant 1981) and at about 4 kpc, where the gas pressure may be 300 $K.cm^{-3}$, the density of this gas phase would be 0.03 cm^{-3}. At very large distances hints to the gas density have been derived from the structure of filaments in the Magellanic-Stream gas. Mirabel, Cohen and Davies (1979) argue that these filaments require an outside pressure of roughly 400 $K.cm^{-3}$ at 50 kpc. With the maximum temperature of 3×10^6 K for bound coronal gas this implies $n(H)=10^{-4}$ cm^{-3}. And so the Milky Way (MW) halo-corona forms, also from the observational point of view, a smooth transition between MW disk and intergalactic space.

The corona could be part of a galactic fountain (Shapiro and Field 1976) and be supported by the hot gas forming the matrix of the Milky Way plane (Cox 1981). Actually, the star-formation rate, the supernova rate, the outflow from the disk and the density in the MW plane form a system which is a self-regulating closed loop (Cox). MHD waves from supernova explosions were proposed as a heating mechanism for the lower galactic halo (Hartquist and Tallant 1981), producing CIV but not requiring the existence of a million-degree corona. The dynamics of the coronal flow was modelled by Bregman (1980), allowing for the possible existence of a galactic wind from the nuclear bulge (Bregman 1981) and producing a net galactocentric flow of the returning cool halo clouds. A net galactocentric motion was noted by dBS83 in the Giovanelli (1980) high-velocity-cloud sample. The cooling volumes, I think, will fragment during descent into clouds. Is CIV the cooling phase of the galactic fountain? The 10^5 K derived from collisional ionization would have a lifetime (cooling) of about 500/n(H) yr (Chevalier 1981). Here I comment that continuous descent would replenish the CIV stage from the top of the corona, resulting in a much longer time where CIV can be detected. NV, with a somewhat longer lifetime, is seen only once (Fitzpatrick and Savage 1983), which has to do with the lesser optical depth of the NV lines (factor 5) and possibly also with smaller than solar abundance (SdB81).

Quasar and intervening-galaxy data may shed light on the actual extent of galaxy halos-coronas. Since the suggestion by Bahcall and Spitzer (1969) the speculations have been underpinned with the Milky-Way halo data. Savage and Jeske (1981) pointed out that the Milky-Way-halo absorbing column densities are similar to those in a particular (but perhaps representative) absorption-line system seen in a quasar spectrum. Hartquist and Snijders (1982) discussed quasar absorption-line statistics and find support for the intervening-corona hypothesis. Bregman and Glassgold (1982) did not see X-ray coronae around galaxies.

REFERENCES

Bahcall, J.N., Spitzer, L.: 1969, Ap. J. 156, L63.
Blades, J.C.: 1981, M.N.R.A.S. 196, 65p.
Bregman, J.N.: 1980, Ap. J. 236, 577.
Bregman, J.N.: 1981, in "The Phases of the Interstellar Medium", Ed. J.M. Dickey, p 191; N.R.A.O.
Bregman, J.N., Glassgold, A.E.: 1982, Ap. J. 263, 564.
Caldwell, J.A.R., Ostriker, J.P.: 1981, Ap. J. 251, 61.
Chevalier, R.A.: 1981, in "The Phases of the Interstellar Medium", Ed. J.M. Dickey, p 175; N.R.A.O.
Cox, D.P.: 1981, Ap. J. 245, 534.
de Boer, K.S.: 1982, in "Highlights of Astronomy" 6, Ed. R.M. West, p 657; Reidel.
de Boer, K.S., Savage, B.D.: 1982, Scientific American 247, no 2 (August).
de Boer, K.S., Savage, B.D.: 1983, Ap. J. 265, 210 (dBS83).

Einasto, J. 1978, in "The Large-Scale Characteristics of the Galaxy", IAU Symp. 84, Ed. W.B. Burton, p 451; Reidel.
Feitzinger, J.V., Kreitschmann, J.: 1982, Astron. Astrophys. 111, 255.
Fitzpatrick, E.L., Savage, B.D.: 1983, Ap. J. 267, 93.
Ginzburg, V.L.: 1978, in "The Large-Scale Characteristics of the Galaxy", IAU Symp. 84, Ed. W.B. Burton, p 485; Reidel.
Giovanelli, R.: 1980, A.J. 85, 1155.
Gondhalekar, P.M., Willis, A.J., Morgan, D.H., Nandy, K.: 1980, M.N.R.A.S. 193, 875.
Habing, H.J.: 1969, B.A.N. 20, 177.
Hartquist, T.W., Snijders, M.A.J.: 1982, Nature 299, 783.
Hartquist, T.W., Tallant, A.: 1981, M.N.R.A.S. 196, 527.
Hulsbosch, A.N.M.: 1978, in "The Large-Scale Characteristics of the Galaxy", IAU Symp. 84, Ed. W.B. Burton, p 525; Reidel.
Lockman, F.J.: 1983, in "Kinematics, Dynamics and Structure of the Milky Way", Ed. W.L.H. Shuter, p 303; Reidel.
McGee, R.X., Newton, L.M., Morton, D.C.: 1983, M.N.R.A.S. 205, 1191.
Mirabel, I.F., Cohen, R.J., Davies, R.D.: 1979, M.N.R.A.S. 186, 433.
Münch, G., Zirin, H.: 1961, Ap. J. 133, 11.
Pettini, M., West, K.A.: 1982, Ap. J. 260, 561.
Prévot, L., et al.: 1980, Astron. Astrophys. 90, L13.
Rohlfs, K., Kreitschmann, J.: 1981, Astrophys. Space Sci. 79, 289.
Savage, B.D., de Boer, K.S.: 1979, Ap. J. 230, L77.
Savage, B.D., de Boer, K.S.: 1981, Ap. J. 243, 460 (SdB81).
Savage, B.D., Jeske, N.A.: 1981, Ap. J. 244, 768.
Shapiro, P.R., Field, G.B.: 1976, Ap. J. 205, 762.
Songaila, A., York, D.G.: 1980, Ap. J. 242, 976.
Spitzer, L.: 1956, Ap. J. 124, 20.
Stecher, F.W.: 1978, in "The Large-Scale Characteristics of the Galaxy", IAU Symp. 84, Ed. W.B. Burton, p 475; Reidel.
Ulrich, M.H., et al.: 1980, M.N.R.A.S. 192, 561.
Wegener, A.: 1911, Physik. Zeitschr. XII, 170.
York, D.G.: 1982, Ann. Rev. Astron. Astrophys. 20, 221.
York, D.G., Blades, J.C., Cowie, L.L., Morton, D.C., Songaila, A., Wu, C.C.: 1982, Ap. J. 255, 467.

DISCUSSION

J.M. Dickey: Is there a strong correlation of column density with $|\mathrm{cosec}\ b|$? Is there strong evidence for a disk-type distribution?

De Boer: The data are insufficient to make such a statement. We know too little.

H. van Woerden: What are the temperatures of the gas seen in the ultraviolet lines? Some HVC cores have such small internal motions that the temperatures there cannot be higher than a few hundred K.

De Boer: Temperatures are not really known. If CIV is in collisional ionization equilibrium, it would be 10^5K. The outer reaches of the corona probably are at a few million K and so the CIV is anywhere between that and your value. The CIV profiles, however, are smooth (see Savage and de Boer 1981), clearly indicating temperatures well over 1000 K. But during descent from far out, recombination may be faster than cooling.

Van Woerden: Unfortunately, the kinetic temperatures I mentioned are upper limits only. There are so far no direct measurements of spin temperatures, derived from comparisons of emission intensities with optical depths of absorption in the spectra of background radio-continuum sources. In fact, we only have lower limits to the spin temperatures.

J. Milogradov-Turin: Do you see asymmetry in the distribution of UV hot gas in galactic coordinates?

De Boer: There are too few lines of sight giving absorption-line information. Anyway, I doubt if an asymmetry would be present. One of van Woerden's slides shows Giovanelli's velocities at positive latitudes; it displays a sine wave structure. The sine form in such a diagram indicates that solar motion is a dominating factor. In one of my slides the run of data points does not go through zero at ℓ = 180°, but 20° away from there. This indicates an average galactocentric motion of order 20-30 km/s in the HVCs (as defined in my paper).

Van Woerden: As to asymmetry in the distribution of high-velocity gas on the sky, I refer to figure 1 in my review paper. The **velocity** pattern shows, to zero order, mirror symmetry about the Anticentre, as expected from galactic rotation, or, more precisely, about $\ell \sim 210°$. But only to zero order; the pattern shows no symmetry in any detail. Also, the **density** distribution is highly asymmetric. This suggests to me that an extragalactic factor (infall of intergalactic gas?) also plays a role.

De Boer: The velocity asymmetry I pointed out is the same thing.

R.D. Davies: It is also visible in the spiral arms in that area.