CORONAE OF THE MAGELLANIC CLOUDS

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A hot gaseous corona was postulated by Spitzer (1956) for the Milky Way as a consequence of the detection of cool interstellar clouds (seen in CaII absorption) on paths to stars in the Milky Way halo. Halos around extra galactic systems were proposed by Bahcall and Spitzer (1969) as a possible explanation for the wealth of high redshift absorption line systems in the spectra of quasars. The recording with the International Ultraviolet Explorer (Boggess et al 1978) in 1978 of echelle spectra of R136 and HD38282 in the LMC showed strong absorption lines of the high ionization stage ions CIV and SiIV, due to material with velocities clearly pertaining to locations outside the Milky Way disk (Savage and de Boer 1979). Thus the reality of the galactic corona became established (review de Boer 1984). There is confusion with the words corona (gas - massive component) and halo (location - stars) and I (1984) proposed for the large mass from dynamics MASsive DArk Component, MASDAC.

From far-UV echelle spectra of stars in the Magellanic Clouds (MC), de Boer and Savage (1980; =dBS80) derived that the pattern of absorption at MC velocities by both neutral and highly ionized gas was similar to that of the Milky Way. This is based on the assumption that gas between us and a MC star has radial velocities correlated with distance from us. It suggested that the MC's may have coronae as well.

1. Observational Aspects

Ultraviolet absorption lines such as CII and MgII have large optical depths and are very sensitive probes for interstellar gas, much more than the CaII, the NaI or 21-cm HI lines. References to UV data papers can be found in Table 1. Observations of visual interstellar absorption lines to MC stars show absorption over widely differing velocity ranges, depending on the direction looked in and the instrumental sensitivity. Blades and Meaburn (1980) detected an extended blue wing in the CaII K profile seen toward R136. Songaila and York (1980) and Songaila (1981) observed MC stars to study the CaII K and NaI D absorption in the MCs. The Magellanic stream was probed by observations of extragalactic objects such as Fairall 9 (see York et al. 1982).

S. van den Bergh and K. S. de Boer (eds.), Structure and Evolution of the Magellanic Clouds. 375–382.

The low ion lines seen in LMC star spectra show a considerable range in absorption velocity, in particular up to 100 km/s less than the radial velocity of the stars (dBS80). Gas velocities more positive than the stellar ones are limited to 30 km/s. For the SMC stars the minimum absorption velocity cannot be determined because of blending by absorption of Milky Way gas, the positive limit is about 70 km/s. One cloud at 300 km/s LSR was found (dBS80; Fitzpatrick and Savage 1983).

The CIV lines pose an interpretational problem. The OB stars may produce some interstellar CIV ions in their immediate vicinity, and that absorption cannot be separated very well from absorption occurring on other portions of the line of sight. In Table 1 data are collected for the CIV absorption due to interstellar material in the MCs and, for comparison, data to Milky Way stars. The strength of CIV seen in the MCs is larger than that in Milky Way gas. Into directions with disturbed material (R136 in the LMC; maybe HD5980 in the SMC; e.g. the Cygnus Loop in the Milky Way) CIV lines are exceedingly strong. However, none of the here listed MC WR stars has a detectable ring nebula (Chu and Lasker 1980). The consistently large strength of the MC CIV lines suggests there is more CIV than from the HII regions or shells alone.

Detailed studies of UV absorption lines, including information from local nebular emission lines, were carried out for R136 by de Boer, Koornneef and Savage (1980), for HD36402 by de Boer and Nash (1982) and for HD5980 by Fitzpatrick and Savage (1983). The R136 region is clearly a-typical for the LMC and has no relevance here. The association to which HD36402 belongs would hardly be able to support a large amount of CIV, if it behaves like a normal (Dyson and de Vries 1972; Weaver et al 1977) interstellar bubble. In that case most of the detected CIV has to be outside the stellar environment. If the CIV absorption seen near the velocity of the nebular lines would be local to the star indeed, there remains otherwise unaccounted for CIV absorption near 220 km/s, a quite different velocity from that of the HD36402 velocity, thus requiring a different explanation. Toward HD5980 the CIV situation is rather confused due to severe velocity blending.

Table 1. Equivalent Widths for Interstellar CIV Lines in MC Stars and Comparable Milky Way Stars

MC star		Sp. Type	V(star)	V(CIV)	W(1550)	Ref	MW star	Sp. Type	W(1550)	Ref
Sk-67 18	--	06-7+WN5	272	240:	200:	dBS	HD153919	06f	90	BKM
Sk-67 5	HD268605	09.7Ib	294	250:	>150:	dBS	HD213087	B0.5Ib	65	BDHR
Sk-67 104	HD 36402	WC5+0B	315	270	200	dBN	HD113904	WC6+09B0I	80:	BKM
Sk-69 246	HD 38282	WN6	245:	210	230	dBS	HD192163	WN6	320	SWW,1
Sk-71 45	HD269676	04-5III	229	220	270	GWMN	HD 46223	04Vf	100	BDHR
Sk-69 243	HD 38268	R 136	245:	215	600	dBS	HD 37022	06+B0.5V	260	FS,2
Sk 108	R31	06.5+WN3	129	150	300	dBS	HD 93403	06f+07.5	150	BKM
Sk 80	---	07Iaf+	---	150	280	dBS	HD 57060	07f	30	BKM
Sk 78	HD 5980	0B?+WN3	---	140	410	dBS	HD190918	WN5+09.5III	470	BKM,1
Sk 159	---	B0Ia	---	170	60	P9	HD152667	B0Ia	75	BKM

Velocities in km/s LSR. Equivalent widths in mÅ
Sk = Sanduleak (LMC 1970, SMC 1968)
dBS = dBS80 and other papers (see de Boer and Savage 1983)
dBN = de Boer and Nash (1982)
GWMN= Gondhalekar et al (1980)
P9 = Prévot et al (1980); Fitzpatrick (1984)

BDHR= Black et al (1980)
BKM = Bruhweiler et al (1980)
FS = Franco and Savage (1982)
SWW = Smith et al (1980)
1: Star in direction of Cygnus SNR
2: V(HI)=-10 km/s, V(CIV)=-30 km/s

Interstellar NV, which essentially cannot be produced by stellar ionization, is seen in absorption in the direction of both HD36402 (de Boer and Nash) and HD5980 (Fitzpatrick and Savage). NV has been detected thusfar at Milky Way velocities only in the spectrum of HD5980. It is not impossible that X rays produce some NV, either directly influencing the temperature structure of the medium or by the Auger process. But most likely the NV exists outside the stellar environment and then indicates the presence of a region of coronal gas around each MC.

Doubt on the reality of the MC coronae proposed by dBS80 was cast by Prévot et al (1980) from the observational point of view. They had collected with the IUE one echelle spectrum of a star in the SMC and found that absorption due to CIV was weak, if present at all. They suggested that dBS80 had underestimated the contribution from the stellar vicinity to the CIV absorption present in the dBS80 spectra. Indeed, the CIV line to this star is weak (see Fitzpatrick, this symposium), but the HII region problem is not clear cut, and it was marked as a potential problem by dBS80.

Feitzinger and Schmidt-Kaler (1982a) compared LMC absorption line velocities available from published UV spectra with Feitzinger's (1980) dynamical model, which is based on all radial velocities available for the LMC. The model results in, among others, a rotation curve which is branched, and Feitzinger argues that there is gas outside the LMC disk, most likely as a warp (see also McGee and Milton 1964). Feitzinger and Schmidt-Kaler then state that all absorption seen in the UV spectra is due to gas either in the disk or in this warp. I think there is a problem with that suggestion. The absorption in the large optical depth lines of low ions occurrs between 200 and 300 km/s for the entire LMC (dBS80), hardly showing effects of rotation. In part the UV absorption velocities coincide (at Feitzingers r<0) with those from the rotation curve, but in other parts (at r>0) the absorption extends to velocities quite different from the rotation curve. The branching of the rotation curve is solely based on the 21-cm data of McGee and Milton (1964, 1966). The velocities producing the branching are from gas in the region south of 30Dor, the data points are projected onto the assumed major axis, and thus have little to do with lines of sight studied by dBS80 and in particular de Boer and Nash. For the SMC Feitzinger and Schmidt-Kaler (1982b) indicate that the absorption components detected coincide with those from 21-cm emission found by Hindman (1967) as well. Again, the UV absorption extends way outside the 21-cm velocities, thus indicating additional absorption from other locations. The CIV lines, hardly mentioned by Feitzinger and Schmidt-Kaler, at first sight follow the low ion lines. However, near the approaching side of the LMC the CIV absorbs at the velocity of the rotation, at the receeding side it absorbs at lesser velocities.

A relevant new development is that both observations (de Boer and Savage 1983) and model calculations for the rotation of the Milky Way halo (Feitzinger and Kreitschmann 1982) show that outside the plane of the Milky Way rotational velocities are much lower than in the disk (see also de Boer 1983). Although the rotation of the LMC cannot be compared directly with that of the Milky Way, one might expect a similar effect in the LMC. At the receeding (NW) side of the LMC one so would expect gas absorption at velocities less positive, at the approaching (SE) side gas absorption at velocities more positive than those of the main rotation curve. That is just what the UV absorption line data show, when compared to the rotation curve of Feitzinger and Schmidt-Kaler. In particular the CIV velocities are of the slow halo rotation type.

Quite extreme velocities were detected in HI 21-cm by McGee, Newton and Morton (1983). Following the call by Savage and de Boer (1981) radio measurements sensitive to very small HI column densities were carried out at Parkes. These show that at almost all positions neutral gas components are seen at a smallest velocity of about 175 km/s and a largest velocity of about 345 km/s LSR. Note that the smallest velocities usually were seen in (UV) absorption as well (see in particular the CII absorption to HD269357 displayed in Savage and de Boer 1981), whereas the largest 21-cm velocities were not seen in absorption. The lower velocity gas indeed is at the near side of the LMC. These data indicate that there is an envelope of hardly rotating HI gas (halo) around the LMC, in which is embedded a rotating "(HI) disk".

Summarizing the observational aspects: the absorption lines of both high and low ionization interstellar ions in the MC star spectra are strong, cover a large range in velocity, mostly at more negative velocities than the stars. New HI data reveal 180 km/s wide velocity ranges of emission from almost all positions of the LMC. The CIV lines are strong, on average stronger than those seen in Milky Way interstellar gas. The bubble theory predicts some CIV, but much less than detected. Absorption by CIV gas has velocities staying behind the main body rotation. The detection of NV is strong evidence for gas of an unusual nature around the MCs.

2. Theoretical Considerations

Following the recognition that much of the volume of interstellar space in the Milky Way is at temperatures of the order of a million K, Shapiro and Field (1976) speculated that stationary conditions may exist with convection of the hot phase of the matrix into the halo regions of the Milky Way. The full balance of heating, mass flux into the halo, and cooling was studied by Cox (1981). The Milky Way indeed may be just capable of maintaining a fountain with a mass flow of > 5 M⊙ per year.

Whether or not a galaxy can maintain a fountain, and thus possibly possesses a hot gaseous corona, depends on the heating and cooling rate of the gas (Cox 1981). The heating is due to supernova (SN) explosions; other energy sources being only of minor importance. The total energy released in the ISM per unit volume is h= 2.Esn/V in erg cm^{-3} s^{-1}, with Esn the energy per SN and V the volume in which this energy is dumped. The cooling is $l=L(T).n(T)^2$ in erg cm^{-3} s^{-1}, where L(T) is the cooling function which is metallicity dependent, and n(T) is the gas density at temperature T. A further requirement is that the ISM is porous, i.e. the hot matrix gas must have a filling factor q, such that the matrix stays hot between successive SN explosions (Cox and Smith 1974). Elaborating an earlier excercise (de Boer 1982) an attempt will be made here to compare the conditions in the LMC and SMC with those in the Milky Way to see if gaseous coronae can exist around the MCs.

The values of the relevant parameters for the Milky Way (MW) are set as follows. The average SN energy E= 10(+51) erg, and with a SN rate of about 1 per 30 years Esn= 10(+42) erg s^{-1} . The volume is taken as a cylinder V= $2\pi R^2$ H with R= 15kpc and scale height H= 100pc (Cox). The heating then is h(MW)= 2 10(+40) erg kpc^{-3} s^{-1} . For the cooling function the curve of Cox may be used. The gas density is derived from the pressure in the disk of 2 10(+4) K cm^{-3}, to be 2 cm^{-3} at 10(+4) K (the intercloud medium). The required porosity q=1 is fulfilled by the Milky Way due to its dependence on the SN influence radius and the disk thickness, q= Rsn/H (Cox).

For the Magellanic Clouds not all these parameters can be determined easily. The energy per SN may be taken the same as that for MW supernovae. The SN rate in the LMC is about 1 per 200 y (Long et al 1981), the rate for the SMC is about one per 1000 y from the fact that the number of SMC SNR is only about 10 (Seward and Mitchell 1981) compared to about 50 for the LMC (Long et al). So Esn(LMC)= 1.6 10(+41) and Esn(SMC)= 3 10(+40) erg s^{-1} (if the average energy per SN is the same as in the MW). The gas volumes and densities into which this energy goes are hard to determine. From the LMC SNR, Long et al estimate gas densities of $0.3 < n(H) < 3.1$ cm^{-3}, and near HD36402 gas densities are 0.4 cm^{-3} in front and 1.6 cm^{-3} in the rear (de Boer and Nash). This suggests a typical n(H)= 1 cm^{-3}, at about 10(+4)K. The disk thickness is uncertain. Since the MCs are smaller but less compact than the MW, a value of 100pc will be adopted. Support for this value may be found from the detection of a pulsar in the LMC (McCulloch et al 1983). Its dispersion measure is 125 cm^{-3} pc which can be reduced to 80 cm^{-3} pc interior to the LMC. The pulsar is near the direction to HD36402 and using the n(e)=0.5 cm^{-3} found there the electron disk would be 150pc thick. For the Milky Way the electron layer is thicker than the HI layer, and thus the H= 100pc for the LMC seems reasonable. Since the entire LMC has SNR's, the entire volume has to be considered, V= $6kpc^3$ based on R= 3kpc. For the SMC the radius is about 1.5kpc, and with equally H= 100pc, V= 1.4 kpc^3 . Thus h(LMC)= 5 10(+40) and h(SMC)= 5 10(+40) erg kpc^{-3} s^{-1} . Considering now cooling, the metallicity of the LMC is about 0.5 that of the MW, for the SMC it is about 0.2 of the MW (see Lequeux et al 1979), reducing the L(T) by the same factor. For the LMC the pressure is about 10(+4) K cm^{-3}, thus a density of about half that of the MW. For the SMC H= 100pc was assumed and with generally double the column density N(H), n(SMC) may be double that of the LMC.

The heating can now be compared for the three systems. From above: h(LMC)= 2.5 h(MW) . (100/H) and h(SMC)= 2.5 h(MW) . (100/H), where the factor 100/H allows to adjust for any better value of the scale height H for each MC. These heating rates are, apart from the value of H, fairly accurate since they derive from reasonably well observed quantities. They suggest that the LMC and SMC have essentially equal heating capacity, but larger than that of the MW. The cooling is less well determined as: l(LMC)= 0.5 l(MW) . $(n(H,LMC)/n(H,MW))^2$ and l(SMC)= 0.2 l(MW) . $(n(H,SMC)/n(H,MW))^2$, where n(MC)/n(MW) shows how the cooling depends on the gas density in each MC compared to the MW. Using the HD36402 area densities from above, l(LMC)= 0.12 l(MW) and from above l(SMC)= 0.2 l(MW). This seems to suggest that the LMC may cool less efficient than the SMC, and both less than the MW. Note, however, that the SMC may have too small a porosity, due to the low SN rate, to maintain matrix gas. But the densities are very uncertain and do not really allow any definite derivations.

Summarizing the theoretical considerations: With the larger rate at which the interstellar medium is heated in the LMC and the SMC, than in the MW, the vigour of the LMC and SMC fountains may be larger than that of the MW. The cooling rates are very poorly determined, basically because of very uncertain mean gas densities in the LMC and SMC; the lower metallicities all by themselves point to a more likely existence of coronae around the MC's than around the MW.

3. Summary and Outlook

Recent observations of interstellar absorption lines in the ultraviolet have given the long expected support for the old proposal that the Milky Way possesses a hot gaseous corona. Related observations in the Magellanic Clouds have shown that it is very likely that these smaller galaxies possess such coronae as well, but the proof is complicated due to blending of absorption from the regions in the immediate vicinity of the MC stars. An extended envelope containing neutral gas (a cool halo) follows from the 21-cm measurements. Theoretical models for the Milky Way interstellar medium including fountain-type flow have been developed only recently and are - of course , but also fortunately - in agreement with what is seen in the MW. The parameters for the MC's needed for similar models are insufficiently known, in particular the density of the gas in the MC's. No firm conclusions for the existence of coronae can be drawn from the energy balance calculations. The high heating rate (compared to the MW) from the known SN rate may point independently to relatively recent extensive star formation. Observing facilities with good photon sensitivity, with spectral resolution of better than 10 km/s, and capable of measuring wavelengths as small as 1000Å are needed. They will allow the detection of ion stages ranging from neutrals such as NaI, over dominant stages such as CII and SiII, to the high temperature ions SiIV, CIV, NV, and OVI, and thus help unravel the structure of the interstellar medium in and around the Magellanic Clouds.

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DISCUSSION

Shull: What are the densities and temperatures in the corona?
de Boer: From the observations one can guess densities after assuming some velocity-distance relation for the gas in the corona. We did so for the Milky Way corona (Savage and de Boer 1979, 1981) but the results are highly uncertain. Temperatures were inferred from comparison with ionization models; the 10^5 K stated there followed when collisional ionization was assumed, but it is not clear at all that the gas is in that state (for a discussion of the Milky Way corona see de Boer 198~~3b~~4). For the Magellanic Clouds nothing is known about the depth of the halo-corona and any density or temperature would be a wild guess.
Feitzinger: The rotation curve of the LMC derived from the new HI survey (Rohlfs, Kreitschmann, and Feitzinger, this Symposium) shows identical features to that of the rotation curve derived from the McGee and Milton data. Again, the velocity space covered by the HI and the absorption lines is the same.
de Boer: That is indeed so. Yet, from the 21-cm data one cannot infer which fraction of the gas is (which velocities come from) behind the stars. The UV data show that the interstellar absorption takes place at velocities mostly smaller than those of the stars. In particular the velocity of the CIV absorption deviates from the main-body rotation curve.
Mathewson: The stars you observed are amongst the hottest in the Magellanic Clouds so that the absorption lines you observe may be produced in their immediate vicinity. For example HD5980 in the SMC is in a nebulosity which is an X-ray source.
de Boer: That is correct and these very concerns were very carefully phrased by us (dBS80). HD5980 indeed is the prime case for such difficulties. Two important aspects of the data, recently more fully discussed by Fitzpatrick and Savage (1983) and by Fitzpatrick (1983 preprint; partly represented at this symposium) are: 1) the ratio of the column densities N(CIV)/N(SiIV) found in the Magellanic Clouds is very similar to the one of the Milky Way corona; and 2) the detection of CIV in Sk159, away from any nebulosity, with a column density small as expected from the lower metallicity of the SMC. Toward other stars there is of course the detection of NV, as discussed in the text.
Gondhalekar: Did you determine any abundances for the gas?
de Boer: For the Milky Way corona gas abundances are a bit lower than solar. For the Magellanic Cloud corona nothing could be derived: For completeness I mention, since you ask, that for the neutral gas in front of R136 some reasonable limiting numbers for Si and Fe could be derived, while the oxygen abundance was found to be a factor 1.7 below solar (de Boer and Nash, Table 2). The latter was derived from the 1356Å OI intercombination line seen in the sum of 5 IUE spectra available at Washburn Observatory at that time. The value agrees closely with the oxygen abundance from HII regions.