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Coronal C^{+3} in the LMC: Evidence for a Hot Halo

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Abstract. Observations of interstellar C IV toward six stars in the Large Magellanic Cloud are described. These data were obtained with the *GHRS* on *HST* and with *IUE*. They provide the first unambiguous evidence that C^{+3} exists in the Large Magellanic Cloud away from regions where it could have been produced locally, as the six stars are of spectral type later than O8, as well as away from hot early-type stars or active regions. Significant differences between the velocities of the C^{+3} absorption and those of Hα emission near the stars shows that these ions are not co-spatial, implying that the C^{+3} originates in the halo of the LMC. It is shown that photo-ionization is unlikely to be the sole source of the C^{+3} and that the LMC halo thus contains hot gas.

1. Motivation

To understand the interstellar medium and how it is shaped by stars, it is necessary to characterize all of its phases at large and small scales. Studies of the LMC have the distinct advantage that a global view can be obtained, while small-scale structure can still be discerned. Other papers in these proceedings present new data on the small- and large-scale distribution of gas with temperatures of 10 K (seen in CO emission), 10^2–10^3 K (seen in H I emission and absorption), 10^4 K (seen in Hα emission) and 10^6 K (seen in X-ray emission).

This paper focuses on the gas at 10^5 K, as observed in absorption in UV resonance lines of highly-ionized atoms such as O^{+5}, N^{+4}, and C^{+3}. Since we can obtain velocity information, it is possible to assess the vertical distribution, unlike what is the case for the 10^6 K gas. The O VI and N V lines are only produced in hot gas. N V tends to have low optical depth, however. O VI cannot be observed by *GHRS*, *STIS* and *IUE*; it will be observed by *FUSE* in the near future. The lines of C IV and Si IV will be present in hot gas, but may also be produced in substantial amounts by photo-ionization (especially Si IV).

Observations of N V and C IV absorption in the Milky Way halo have been interpreted as evidence for some form of the galactic fountain (Savage et al. 1997). The 10^5 K gas in the LMC was studied by Chu et al. (1994), who concluded that it occurs in all superbubbles and supergiant shells, but that there was insufficient evidence to infer the presence of a hot halo. Such a halo is expected to be present if the hot gas inside bubbles and shells can break out and redistribute itself across the LMC. This provides a mechanism to homogenize the metal abundances in the ISM; without redistribution stars born at the same time in well-separated clusters might have large differences in metallicity.

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2. Previous Observations

The first discussion of C IV absorption in the LMC halo was presented by de Boer & Savage (1980) and de Boer & Nash (1982). They had relevant data for two SMC stars and one LMC star (Sk−67 104 in N 51 D). All three were inside a bright H II region, and all showed interstellar absorption by highly-ionized atoms. A number of arguments were presented to conclude that some of the C IV absorption is related to a halo, including: (a) in other LMC and Milky Way stars in H II regions narrow lines of Si II* are found, but not in the three stars in question; (b) the C IV lines are broader than lines associated with the H II region; (c) the standard wind-blown bubble model (Weaver et al. 1977) predicts much lower column densities.

However, we now know that N 51 D also has strong X-ray emission, which is not expected for a wind-blown bubble but can be explained by off-center SNRs (Chu & Mac Low 1990); this also increases the expected strength of the high-ionization absorption. Further, Prévot et al. (1980) argued that a star in the SMC outside an H II region did not show C IV absorption, although Fitzpatrick (1984) found C IV in a deeper spectrum. Savage (1984) mentioned C IV absorption in the star Sk−67 147a, a B0.5 star outside an H II region, incapable of producing photo-ionized C^{+3}.

However, Chu et al. (1994) showed that C IV absorption is seen in all stars of type earlier than O7, all stars in superbubbles, and all stars in supergiant shells (such as Sk−67 147a in LMC 3). The only stars without interstellar C IV were Sk−67 05 and possibly Sk−67 111 and Sk−68 114, all of which were in the field. This showed that previous studies did not *conclusively* show that the LMC has hot halo gas, as in all cases it was possible to argue that the observed C IV absorption might be associated with more local phenomena.

3. Procedure to Detect Hot Halo Gas

One of the conclusions of Chu et al. (1994) was that to unambiguously detect hot gas in the LMC halo it is necessary to select stars with a low a-priori probability of having highly-ionized gas nearby. This excludes stars in superbubbles and supergiant shells, where supernovae may locally produce hot gas. It also excludes stars of type earlier than O7, which can photo-ionize C^{+2} (although not O^{+4} and N^{+3}). Stars later than B2 are also bad because of the increasing amount of stellar absorption lines.

To find probe stars fitting these criteria, the Sanduleak catalogue of LMC early-type stars and its updates were used for spectral types and magnitudes. For each star the spectral type gives an estimate of T_{eff}. A Kurucz stellar atmosphere model for the temperature was then combined with the star's visual magnitude to predict the flux at 1550 Å and at 1035 Å. Requiring an S/N of >10 in the continuum, in practice about 100 stars are bright enough to observe halo C IV absorption, 170 to observe halo O VI.

Even if high-ionization absorption would be seen in such a halo probe, it is not necessarily true that this absorption originates in the LMC halo: it could be from the disk near the star. To settle this question we further need to observe the velocity of the Hα emission near the star, which should originate in the

LMC disk. If the velocities are the same, the warm and highly-ionized gas are probably co-spatial. Only if these velocities are different can we conclude that the C IV probably originates in a halo.

After showing that the highly-ionized gas occurs in the halo, it must be shown that photo-ionization is not the major producer. The models of Bregman & Harrington (1986) predict that the fraction of C in the form of C IV will be f(C IV)$\sim$0.1 for densities below $n_x \sim 10^{-3}$ cm^{-3}. So, assuming an exponential halo with scaleheight H, N(C IV) can be estimated as f(C IV) A(C) n_x H $\sim 3\times10^{13}$ H(kpc) cm^{-2}, where A(C) is the abundance of carbon ($\sim 10^{-4}$ in the LMC). In the Milky Way, H is $\sim$4.5 kpc (Savage et al. 1997). Although there are no direct estimates, in the LMC H can be expected to be smaller than that, since the diameter of the ISM in the LMC is only about 5 kpc.

4. Results from GHRS

In *HST* cycle 5 we obtained C IV spectra for 5 stars, at about 15 km s^{-1} resolution, having a S/N ratio of $\sim$10. We further used the 4-m telescope at CTIO to observe the Hα emission near the stars. Figure 1 shows the resulting continuum-normalized spectra. The table below presents the measured column densities.

Table 1. Measured properties of C IV absorption.

Star	λ_0	Milky Way			LMC				
		v	W	N	v	W	N	v(Hα)	diff.
		km/s	km/s	cm^{-2}	km/s	km/s	cm^{-2}	km/s	km/s
Sk−67.05	1548	...	...	...	...	...	<3.0		
	1550	64	28	10.9	...	...	<2.1		
Sk−67.46	1548				272	80	9.1	289	−23
	1550	20	42	6.4	260	78	11.5		
Sk−67.76	1548	30	75	9.0	254	42	6.9	316	−59
	1550	25	45	8.7	259	54	6.7		
Sk−69.59	1548	37	75	12.1	256	59	7.1	281	−26
	1550	42	78	12.9	254	57	7.3		

Interstellar C IV absorption associated with both the Milky Way and the LMC is clearly detected in the spectra of Sk−67 46, Sk−67 76 and Sk−69 59. The flux of Sk−70 96 was much lower than expected, but C IV λ1550 is present. Stellar absorption hides C IVλ1548. The spectral type of Sk−69 110 was found to be B3Ia, rather than B1 as originally assumed; the interstellar lines are therefore hard to discern. A good non-detection is found for the LMC absorption toward Sk−67 05, the table gives the 5-σ detection limit.

The measurements lead to the following conclusions:

1. Our stars were selected to be away from regions where C^{+3} can be easily produced by LMC stars, supernova shocks, or stellar photo-ionization. Strong C IV absorption is still seen, however.

2. Since the velocity of Hα emission and C IV absorption near the star differ, not all of the C IV absorption originates in the LMC disk.

3. Photo-ionization is not the main producer of C^{+3} in the LMC.

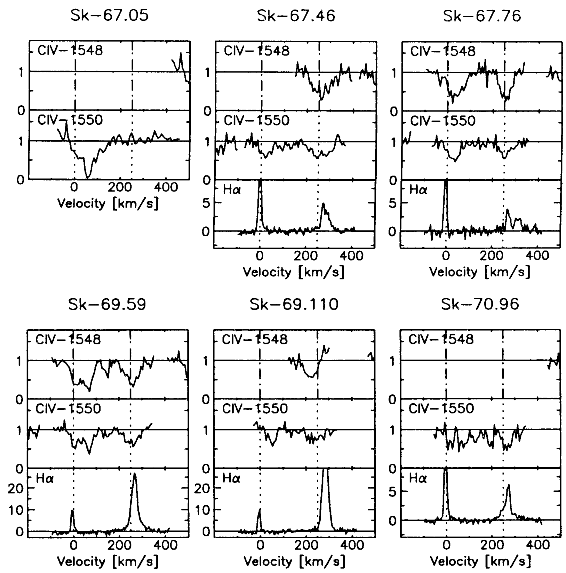

Figure 1. Continuum-normalized C IV and Hα spectra.

4. Combining 1), 2) and 3) we conclude that the LMC has a hot gaseous halo.

5. There are large variations in N(C IV): a factor 2 betweeen detections, down to zero toward Sk−67 05.

6. The column density range in the LMC is similar to that in the Milky Way: $9\text{–}16\times10^{13}\,\mathrm{cm}^{-2}$ vs $8\text{–}14\times10^{13}\,\mathrm{cm}^{-2}$.

7. As the carbon abundance in the LMC is lower than that in the Milky Way, a higher percentage of carbon is in the form of C^{+3}, which can easily be understood in cooling flow models such as the galactic fountain.

A more complete discussion of this work is given by Wakker et al. (1998).

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Discussion

Daniel Wang: In the field of the LMC, there must be some bright, nearby QSOs that could be used for FUV absorption studies. Are you aware of any such work?

Wakker: So far there are no known AGNs toward the LMC bright enough ($V < 15$) to observe at sufficiently high spectral resolution (15 kms^{-1}). For fainter AGN's impractically long integration times will be needed even if the resolution requirement is relaxed.

Nicholas Suntzeff: There is no evidence for a kinematical halo in the LMC. Does this mean that the "halo" of hot gas you are discussing has no stellar component?

Wakker: Yes, it is a gaseous halo, such as the MW has too, possibly formed by the cumulative effect of star formation that pushes gas out.

Robin Shelton: Can you constrain the filling factor of the CIV-rich gas?

Wakker: Not really, since we do not know the actual volume densities and path lengths.

Robin Shelton: Your last overhead specified that the CIV gas was 10^5 K. Is that from a constraint or can the gas be cooler but not yet recombined?

Wakker: Will be in the paper.

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