Interstellar O VI in the Large Magellanic Cloud

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Abstract. I summarize Far Ultraviolet Spectroscopic Explorer (FUSE) observations of interstellar O VI absorption towards 12 early-type stars in the Large Magellanic Cloud (LMC), the closest disk galaxy to the Milky Way. LMC O VI is seen towards all 12 stars with properties (average column densities, kinematics) very similar to those of the Milky Way halo, even though O/H in the LMC is lower by a factor of \(\sim 2.5\). Sight lines projected onto known LMC superbubbles show little enhancement in O VI column density compared to sight lines towards quiescent regions of the LMC. The O VI absorption is displaced by \(\sim -30 \text{ km s}^{-1}\) from the corresponding low-ionization absorption associated with the bulk of the LMC gas. The LMC O VI most likely arises in a vertically-extended distribution, and I discuss the measurements in the context of a halo composed of radiatively-cooling hot gas. In this case, the mass-flow rate from one side of the LMC disk is of the order \(\dot{M} \sim 1 \text{ M}_\odot \text{ yr}^{-1}\).

1 Introduction

The production of hot, highly-ionized gas in galactic environments is closely related to the input of energy and matter from stars and supernovae into the interstellar medium (ISM). Such “feedback” can shape the ISM on kiloparsec scales in regions with high concentrations of early-type stars. In disk galaxies, with differing pressure gradients in the vertical and radial directions, such energy input is responsible for the production of vertically-extended “halos” or “coronae” about these systems [1, 2].

Howk et al. [3] have recently completed a study of interstellar O VI in the Large Magellanic Cloud (LMC). Because the ionization energy required for its creation (\(\text{IP}_{\text{OVI}} = 114 \text{ eV}\)) precludes its production via photoionization by starlight, O VI is a tracer of hot (\(\sim 3 \times 10^5 \text{ K}\)), collisionally-ionized gas in galactic environments. Therefore, the Howk et al. study of O VI in the LMC provides fundamental information on the content, distribution, and kinematics of material created by the interactions of stars and supernovae with the ISM in the closest and best-studied disk galaxy beyond the Milky Way. I summarize the principle results of this study below.

2 LMC O VI – Content and Kinematics

Table 1 summarizes the statistical properties of the O VI column densities, \(N(\text{O VI})\), along the 12 sight lines in the Howk et al. [3] study, while Figure 1 compares the distribution of LMC O VI with Hα [4] and ROSAT hard X-ray
Figure 1: Hα image (left) of the LMC [3] and 0.5-2.0 keV ROSAT PSPC mosaic (right) of the LMC [3] with positions of the FUSE probe stars marked. The radius of each circle is linearly proportional to the column density of O\textsc{vi} at LMC velocities (scale given in the upper right).

Significant O\textsc{vi} is observed across the whole face of the LMC, although the O\textsc{vi} is patchy: the standard deviation of the measurements is 38% of the mean. Sight lines projected onto known superbubbles (the four sight lines south of $\delta = -68^\circ$ in Figure 1) show only very modest (if any) O\textsc{vi} enhancements compared with more quiescent-appearing sight lines (e.g., Nos. 1–4 in Figure 1).

Table 1. Statistical Properties of Interstellar O\textsc{vi} in the LMC

| Quantity | Value |
|----------|-------|
| $\langle N(\text{O\textsc{vi}}) \rangle$ | $2.34 \times 10^{13}$ cm$^{-2}$ |
| $\sigma[N(\text{O\textsc{vi}})]$ | $0.89 \times 10^{14}$ cm$^{-2}$ |
| $\langle N_\perp(\text{O\textsc{vi}}) \rangle$ | $1.95 \times 10^{14}$ cm$^{-2}$ |

For comparison with the Milky Way values reported by Savage et al. [7], we define the quantity $N_\perp(\text{O\textsc{vi}}) \equiv N(\text{O\textsc{vi}}) \cos i$, where $i$ is the inclination of the LMC. This is the column density projected perpendicular to the plane of the LMC and is equivalent to the $N_\perp \equiv N \sin |b|$ measurements in the Galaxy. The first FUSE measurements of Galactic halo O\textsc{vi} towards extragalactic objects found $\langle N(\text{O\textsc{vi}}) \sin |b| \rangle = 14.29$ (38% standard deviation). The average LMC and Milky Way $N_\perp(\text{O\textsc{vi}})$ values – and their standard deviations – are identical.
Figure 2: The observed absorption line profiles of O\textsc{vi} λ1031.926 (thick line) and Fe\textsc{ii} λ1125.448 (thin line) towards the LMC stars studied in Howk et al.\cite{1}. The Fe\textsc{ii} absorption components associated with the Milky Way (v < +175 km s\(^{-1}\)) and LMC (v > +175 km s\(^{-1}\)) are seen to be significantly narrower than the corresponding O\textsc{vi} profiles.

The observed kinematic profiles of the LMC O\textsc{vi} are quite broad, with breadths implying \(T < (2 - 5) \times 10^6\) K. Figure 2 shows the normalized O\textsc{vi} absorption profiles along the 12 sight lines studied and the profiles of a moderate-strength Fe\textsc{ii} transition. The latter traces gas associated with neutral material in the LMC disk. The O\textsc{vi} is much broader than the Fe\textsc{ii} along all sight lines and is systematically blue-shifted from the disk (by ~ 30 km s\(^{-1}\) on average). Thus, the O\textsc{vi} is kinematically decoupled from the bulk of the LMC disk material. There is gas present at velocities compatible with the outflow of material from the LMC disk along all of the sight lines discussed by Howk et al. In only two cases is there possibly O\textsc{vi} at velocities that may indicate infall.

3 Interpretation

The \textit{FUSE} observations reveal interstellar O\textsc{vi} associated with the LMC is present in large quantities across the whole face of the LMC, with an average column density and patchiness identical to those of the Galactic halo. Lines of sight projected onto superbubbles and supergiant shells have much the same column densities as lines of sight projected onto quiescent regions. The LMC O\textsc{vi} absorption is both much broader and shifted to lower absolute velocities.
than the lower-ionization gas (e.g., Fe II).

For reasons discussed in detail by Howk et al. [4], the favored interpretation of these salient aspects of the LMC O VI is that the LMC is surrounded by a hot, highly-ionized halo or corona – similar in many respects to that found in the Milky Way – that gives rise to the observed O VI absorption. Several models can explain the physics of the O VI production within a gaseous halo about the LMC, including cooling galactic fountain flows and interface models (such as turbulent mixing layer or conductive interface models).

The cooling fountain model provides an elegant explanation for the similarity of the average Milky Way and LMC O VI column densities. Though these galaxies differ in oxygen abundance by a factor of $\sim 2.5$, the column density of highly-ionized metals in a cooling flow of hot material is independent of abundance [2]. The column density of O VI in the Edgar & Chevalier [2] models is a function of the ratio $N/n_0$, where $N$ is the cooling rate (in protons cm$^{-2}$ s$^{-1}$), and $n_0$ is the initial density of the flow. The average LMC O VI column density (Table 1) corresponds to a one-sided mass-flow rate from the LMC disk of

$$\dot{M} \sim 1 \left( \frac{n_0}{10^{-2} \text{ cm}^{-3}} \right) M_\odot \text{ yr}^{-1}.$$  

The adopted density is consistent with estimates of electron densities in supergiant shells and diffuse gas using X-ray observations of the LMC [6].

It should be noted, however, that the energy input requirements into the ISM and mass flow rates from the disk can be significantly different if the O VI arises in turbulent mixing layers or other interface-type models. Observations of other highly-ionized species (e.g., C IV) will be required to distinguish between the cooling flow and interface models.

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