O VI Emission from the Supernovae-regulated Interstellar Medium: Simulation versus Observation

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Abstract

The O VI λλ1032, 1038 Å doublet emission traces collisionally ionized gas with \( T \approx 10^{5.5} \) K, where the cooling curve peaks for metal-enriched plasma. This warm-hot phase is usually not well-resolved in numerical simulations of the multiphase interstellar medium (ISM), but can be responsible for a significant fraction of the emitted energy. Comparing simulated O VI emission to observations is therefore a valuable test of whether simulations predict reasonable cooling rates from this phase. We calculate O VI λ1032 Å emission, assuming collisional ionization equilibrium, for our small-box simulations of the stratified ISM regulated by supernovae. We find that the agreement is very good for our solar neighborhood model, both in terms of emission flux and mean O VI density seen in absorption. We explore runs with higher surface densities and find that, in our simulations, the O VI emission from the disk scales roughly linearly with the star formation rate. Observations of O VI emission are rare for external galaxies, but our results do not show obvious inconsistency with the existing data. Assuming the solar metallicity, O VI emission from the disk in our simulations accounts for roughly 0.5% of supernovae heating.

Key words: galaxies: evolution – galaxies: formation – galaxies: ISM – ISM: kinematics and dynamics

1. Introduction

Supernova (SN) explosions represent a key form of stellar feedback in galaxies, and produce copious hot gas in the ISM. The SN energy can regulate the ISM dynamics and launch galactic outflows (Cox & Smith 1974; McKee & Ostriker 1977; Cox 2005). One key factor to quantify the efficiency of SN feedback is the energy loading factor (or “thermalization factor”), which is the fraction of SN energy that is loaded into the outflows. The efficiency of radiative cooling in the multiphase ISM directly affects this loading efficiency.

A temperature around \( 10^{5.5} \) K is where the cooling curve peaks for metal-enriched gas (e.g., Sutherland & Dopita 1993). The O VI λλ1032, 1038 Å doublet is one major coolant around this temperature. These O VI resonant lines have been observed widely, from the local ISM, which provides the first strong evidence of the prevalence of the hot phase in the ISM (Jenkins & Meloy 1974; York 1974), to the circumgalactic medium (CGM) and even the intergalactic medium (e.g., Simec et al. 2002; Bregman et al. 2006; Tumlinson et al. 2011). Most of these observations, though, focus on absorption instead of emission, except for the solar neighborhood (e.g., Otte et al. 2003). The origin of gas around this temperature is not totally clear. Thermal conduction/turbulent mixing at the interface between the hot plasma \( (T \gtrsim 10^6 \text{K}) \) and warm clouds \( (T \sim 10^4 \text{K}) \) (McKee & Ostriker 1977; Weaver et al. 1977; Cowie et al. 1979; Begelman & Fabian 1990), and cooling from hotter gas (Edgar & Chevalier 1986; Slavin & Cox 1993; Dopita & Sutherland 1996; Heckman et al. 2002) have been suggested as possible mechanisms.

In hydrodynamic simulations of astrophysical systems, the quantity of gas around \( 10^{5.5} \) K can be affected by numerical mixing and diffusion. Depending on the resolution and technique used, hydrodynamic simulations can artificially promote or suppress the mixing and the amount of gas in the warm-hot phase. For example, the particle-based SPH scheme usually exhibits too little mixing, while the mesh-based techniques can have too much mixing (Agertz et al. 2007; Springel 2010). The magnitude of this numerical artifact is hard to gauge. This is a particular issue when multiple phases—e.g., Simcoe et al. 2006; Otte & Dixon 2006; Welsh et al. 2007. For external galaxies, the O VI interstellar absorption line is typically only observed in a few cases (e.g., Sutherland & Dopita 1993; Cowie et al. 1979; Begelman & Fabian 1990). The O VI line emission has also been detected in various sight lines (Dixon et al. 2006; Otte & Dixon 2007; Welsh et al. 2007). For external galaxies, the O VI interstellar absorption line is seen in nearly every starburst system observed (e.g., Grimes et al. 2007). The CGM around star-forming galaxies shows absorption of O VI out to \( \gtrsim 100 \text{ kpc} \) (Tumlinson et al. 2011).

O VI emission from the disk or the CGM, on the other hand, has only been reported in a few cases (Otte et al. 2003; Grimes et al. 2007; Hayes et al. 2016).
In this Letter, we calculate the emission of OVI 1032 Å as well as the O VI column densities, for our ISM simulations with SN feedback. de Avillez & Breitschwerdt (2005, 2012) simulated the SNe-regulated ISM for the solar neighborhood, and found OVI absorption agreeing well with the observations. We extend that study by calculating both the emission and the column density, for conditions with various star formation rates. We describe the simulations and calculation of OVI emission in Section 2, show the results and compare with the observations in Section 3, and summarize in Section 4.

2. Methods

The simulations presented in this paper are the four fiducial runs in Li et al. (2016), hereafter referred to as Paper I. We briefly introduce the setup here; for details, see Paper I.

Our simulations are performed using the Eulerian hydrodynamic code Enzo (Bryan et al. 2014). We use the higher-order piecewise parabolic method (PPM; Colella & Woodward 1984) as the hydro-solver, along with the two-shock Riemann solver. The 3D, rectangular simulation boxes cover a fraction of the galaxy disk, with a square cross-section and the long z-axis perpendicular to the disk plane. Similar configurations have been widely adopted (e.g., Dib et al. 2006; Joung & Mac Low 2006; Creasey et al. 2013; Walch et al. 2015; Kim et al. 2017). The four runs discussed in this paper have initial gas surface densities $\Sigma_{gas}^1 = 1, 10, 55, 150 \, M_\odot \, \text{pc}^{-2}$, respectively, for the four fiducial runs, such that the combinations of $(\Sigma_{gas}, \Sigma_{SFR})$ fall along the observed correlation for nearby galaxies at a kiloparsec scale (Kennicutt 1998; Bigiel et al. 2008, see Figure 1 of Paper I). The SN rate is related to $\Sigma_{SFR}$ by assuming one SN explodes per $150 \, M_\odot$ of star formation. SNe are placed randomly in the disk, with a scale height of 150 pc for core-collapse SNe (90%), and 325 pc for SNe Ia (10%). SNe are injected with $10^{51}$ erg thermal energy within a sphere. We use a cooling curve for the solar metallicity gas with a low-temperature cutoff at $T = 300$ K, which assumes a collisional ionization equilibrium (CIE) above $10^4$ K (Rosen & Bregman 1995). We apply photoelectric heating that scales linearly with the $\Sigma_{SFR}$. For the detailed model parameters, see Table 1 of Paper I. We do not explicitly include thermal conduction.

To calculate the O VI density and emission, we assume CIE. The relative abundance of O/H is $5 \times 10^{-4}$ by number (the “solar abundance” in this paper). The fraction of O in the ionization stage of $+5$, as a function of temperature, is taken from Sutherland & Dopita (1993). The collision strength for O VI $2s \, ^2S - 2p \, ^2P$, the transition of which results in the 1032, 1038 Å emission, is 5.0 (Osterbrock 1989). The emission flux of the 1032 Å line is twice that of 1038 Å.

3. Results

3.1. O VI-emitting Gas in Simulations

We illustrate the distribution of O VI-emitting gas in simulations in both real and phase space. Figure 1 shows slices of temperature and O VI photon emissivity from the midplane of the solar neighborhood model $\Sigma_{10}$-KS. O VI emission mainly comes from the boundary between the hot and cool medium. The O VI-emitting gas is usually not well-resolved, with some emitting regions resolved by one computational cell. The dimensions are 350 pc $\times$ 350 pc, and the resolution is 2 pc. The color-coding for the lower panel has a floor at $10^{-20} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{cm}^{-2}$.

Figure 1. Slices of temperature and O VI 1032 Å photon emissivity from the midplane of the solar neighborhood model $\Sigma_{10}$-KS. O VI emission mainly comes from the boundary between the hot and cool medium. The O VI-emitting gas is usually not well-resolved, with some emitting regions resolved by one computational cell. The dimensions are 350 pc $\times$ 350 pc, and the resolution is 2 pc. The color-coding for the lower panel has a floor at $10^{-20} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{cm}^{-2}$.

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0.01–0.1 cm$^{-3}$, contributes most of the emission. Below $1.5 \times 10^5$ K and above $10^6$ K, the emission is negligible.

### 3.2. O VI in the Solar Neighborhood

Figure 3 shows the integrated flux along the x- and the z-directions for the O VI 1032 Å emission. The snapshot is taken at $t = 140$ Myr for the run $\Sigma 10$-KS. Most of the emission is from near the midplane, where gas is dense and where most SNe explode. Above the plane, gas is mostly hot ($T > 10^6$ K), and the oxygen atoms are ionized even further. It is generally the case that most of the emission is from near the disk in our simulations. Indeed, Hayes et al. (2016) found emission from the SF disk is much stronger than that from the halo. The 1032 Å emission outside of the disk is seen in and around the clouds. The hot gas can shock-heat and ablate the warm clouds, as well as mix with them, all of which may result in gas around $10^{5.5}$ K. The x-projection of the emission shows some spatial variation. The regions where the emission is weaker have smaller gas column densities, as a result of hot, low-density bubbles that connect to the halo.

The FUSE satellite has surveyed O VI 1032 Å emission from the local ISM at various Galactic latitudes (Dixon et al. 2006; Otte & Dixon 2006). The emission is detected for about 40% of sight lines, with intensities of $(1.9–8.6) \times 10^3$ photon s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Welsh et al. (2007) used the SPEAR satellite to look at the north Galactic pole region, and detected O VI 1032 Å emission from 8 out of 16 survey regions, with intensities of $5 \times 10^3–2 \times 10^4$ photon s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Note that the observed emission may be partly from the CGM, so these values may be an upper limit for the emission from near the disk. Our projection plot along the z-direction shows 1032 Å emission of $(0.5–6) \times 10^3$ photon s$^{-1}$ cm$^{-2}$ sr$^{-1}$, broadly consistent with the observations. (The emission in the simulations includes the two sides of the midplane, whereas the observation is from within the plane, so there is a factor of $\sim 2$ difference.)

In addition to emission, we also briefly touch on O VI absorption. Our results show very good agreement with the observations. Absorption-line studies from stars with known distances reveal that the local O VI density $n_{O VI}$ in the disk to be about $(2.2 \pm 1.0) \times 10^{-8}$ cm$^{-3}$ (Jenkins 1978b; Oegerle et al. 2005; Savage & Lehner 2006; Bowen et al. 2008; Barstow et al. 2010). The $n_{O VI}$ in our solar neighborhood run is $(2.4 \pm 0.3) \times 10^{-8}$ and $(1.8 \pm 0.3) \times 10^{-8}$ cm$^{-3}$, averaged over $|z| \leq 100$ and 200 pc, respectively.

The non-equilibrium effects will affect these results, generally by boosting the amount of O VI at lower temperatures. Recent simulations by de Avillez & Breitschwerdt (2012), which track the ionization stage of oxygen, i.e., relaxing the assumption of CIE, find that up to 70% (by mass) of the O VI may be at $T \lesssim 10^5$ K, although their mean $n_{O VI}$ is consistent with ours. We expect that the non-equilibrium
effects will affect the O VI absorption more strongly than emission, since low temperatures would lead to less efficient collision and excitation.

3.3. Scaling of O VI with SFR

Figure 4 shows the O VI 1032 Å emission, integrated over the z-direction, as a function of $\Sigma_{\text{SFR}}$. The quantity is averaged over the 1-x-y plane. The error bar shows the time variation. We find the O VI emission scales roughly linearly with $\Sigma_{\text{SFR}}$. As mentioned before, the solar neighborhood model agrees well with the observations.

Observations of O VI emission from external galaxies are limited to a few cases. We show the emission from SDSS J1156+5008 (Hayes et al. 2016). The surface brightness reported in that paper is for the 1038 Å line. To get that of the 1032 Å, we have applied (i) a factor of 2 increase due to the relative intensity of 1032 and 1038 Å; and (ii) a factor of 2 increase to account for gas from both sides of the disk, since only the redshifted part is observed as emission. We have also scaled the emission to the solar abundance. Hayes et al. (2016) calculated O/H using two methods, which differ by a factor of ~3. The two hollow triangles in the plot correspond to these two O/H values. Still, the observed surface brightness is likely a lower limit of the real emission for several reasons. First, the aperture of the COS spectrograph is 2.5 arcsec in diameter, corresponding to a physical scale of $r \sim 9.4$ kpc at the galaxy’s redshift (0.235). The surface brightness of the 1038 Å line is assumed to be uniform inside the aperture, but the star-forming region is very compact—only about 1 kpc across (as seen from HST). Thus the actual surface brightness in this starbursting region is probably higher. Second, the 1038 Å line can be partially blended with the nearby C II absorption. Additionally, attenuation by dust in the host galaxy, especially in the disk, can also lower the emission. Based on these arguments, the reported emission intensity is probably a lower limit. Also, the CGM probably does not contribute much to the surface brightness in this measurement, since for J1156, the O VI emission in the halo is observed, with an intensity much smaller than the center.

Apart from J1156, another galaxy, Haro 11, turns out to be very similar (Grimes et al. 2007; Hayes et al. 2016). Hayes et al. (2016) also compare J1156 with the stacked spectra of other starbursting galaxies from archival data, and find an O VI emission comparable to J1156.

For high $\Sigma_{\text{SFR}}$, we cannot yet draw a firm conclusion about whether our results are consistent with the (very limited) observations. There can be agreement if, for the very high $\Sigma_{\text{SFR}}$ cases, the actual emission is above the observed value for the reasons discussed above, and/or the O VI emission from the simulations increases more slowly for higher $\Sigma_{\text{SFR}}$, which we do not cover in our simulations.

Finally, the roughly linear scaling of the O VI surface brightness with $\Sigma_{\text{SFR}}$ implies that the cooling rate from O VI is an approximately constant fraction of the SNe heating. We find this fraction to be around 0.5%, including both 1032 and 1038 Å. Therefore cooling from O VI is not an important source of energy loss. Most (>80%) cooling of the ISM comes from a broad warm-hot regime: $10^5$–$10^7$ K. But O VI mainly exists within a narrow fraction of it: $10^5.3$–$10^5.6$ K; gas in this temperature range only contributes to a few percent of the total cooling rate.

The predicted O VI column density $N_{\text{O VI}}$ (across the whole z-direction), as a function of $\Sigma_{\text{SFR}}$, is shown in Figure 5 (purple stars). The column density is averaged over the x-y plane. The error bar indicates the time variation. The correlation of $N_{\text{O VI}}$ with $\Sigma_{\text{SFR}}$ is positive but the dependence is weak, with a power-law index of 0.19. For four orders of magnitude span in $\Sigma_{\text{SFR}}$, $N_{\text{O VI}}$ only differs by a factor of 6. For the solar neighborhood, we show the observed value as in Bowen et al. (2008; orange box), with a factor of 2 increase applied to include O VI from both sides of the galaxy disk; the vertical
range of the box indicates the statistical variation of $N_{\text{OVI}}$, and the horizontal range denotes the uncertainty of $\Sigma_{\text{SFR}}$. Our result generally agrees with the observation.

Grimes et al. (2009) have reported $N_{\text{OVI}}$ for 12 starburst galaxies (from absorption against galaxy disks). We plot these $N_{\text{OVI}}$ together with the corresponding $\Sigma_{\text{SFR}}$ (Table 1 of Heckman et al. 2015). We apply a factor of 2 increase to the data to account for O VI from both sides of the disk, and scale $N_{\text{OVI}}$ to the solar abundance. Additionally, we plot $N_{\text{OVI}}$ for J1156 (Hayes et al. 2016). Those starburst systems have $N_{\text{OVI}}$ that are usually an order of magnitude larger than (the extrapolation of) our results. But note that a significant fraction of $N_{\text{OVI}}$ can come from the CGM. For nearby Milky Way-like galaxies, $N_{\text{OVI}}$ of the CGM (from absorption against background quasars) ranges from $10^{14}$ to $10^{15}$ cm$^{-2}$ (Werk et al. 2016). The starburst systems may have even higher $N_{\text{OVI}}$ in the CGM for their much stronger SF/outflows activities. If O VI in the CGM indeed dominates the column density, then the extrapolation of our results may be consistent with observations.

We tested the effect of resolution for the two low-$\Sigma_{\text{gas}}$ cases. The test runs include a midplane resolution of 4 pc for $\Sigma_{10}$-KS (fiducial 2 pc), and 2.5 pc and 10 pc for $\Sigma_{1}$-KS (fiducial 5 pc). The 1032 Å emission agrees within the time variation (which can be as large as 80%). The mean values of O VI emission increase with improved resolution. Such a trend can be partly attributed to the fact that resolving more cloud fractals increases the total area of boundary layers. The convergence rate is faster for $\Sigma_{1}$-KS than $\Sigma_{10}$-KS; improving resolution by a factor of 2 leads to 20% and 60% increase of the mean O VI emission, respectively. The total cooling rate shows less time variation (~20%), and is consistent for different resolutions as well.

4. Conclusions

In this Letter we calculate the O VI 1032 Å emission from our ISM simulations with SN feedback. This is done to test the radiative cooling from gas with $T \sim 10^{5.5}$ K (which cools very efficiently but is usually not very well-resolved in simulations) against observations. We find that, for the solar neighborhood, our results agree well with the observations, both in terms of emission flux and mean O VI density in absorption. Most emission comes from the gas disk. The relatively dense (0.01–0.1 cm$^{-3}$) gas around the interface between hot gas and warm clouds contributes the major part of the emission.

Changing $\Sigma_{\text{gas}}$ and $\Sigma_{\text{SFR}}$ along the Kennicutt relation, we find that both $N_{\text{OVI}}$ and the O VI surface brightness increase with $\Sigma_{\text{SFR}}$. For $N_{\text{OVI}}$, the dependence is quite weak, while the surface brightness of O VI emission scales roughly linearly with $\Sigma_{\text{SFR}}$. O VI emission is approximately 0.5% of the SNe heating rate. It cannot yet be determined definitely whether our results give a reasonable emission for high $\Sigma_{\text{SFR}}$, because of the limited observational and numerical samples, although agreement is not unlikely. More observations of the O VI emission, for both low and intermediate-high $\Sigma_{\text{SFR}}$, are needed for a more complete comparison.

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