Do cooling and heating functions actually exist?

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ABSTRACT

Cooling and heating functions describe how radiative processes impact the thermal state of the gas as a function of its temperature and other physical properties. In a most general case they depend on the detailed distributions of level populations of numerous ionic species and on the radiation spectrum. Hence, these functions may vary on a very wide range of spatial and temporal scales. In this paper, we explore cooling and heating functions between 5 ≤ z ≤ 10 in simulated galaxies from the Cosmic Reionization On Computers (CROC) project. We find that the actual cooling (heating) rates experienced by the gas at different temperatures in the simulations do not correspond to any single cooling (heating) function. Gas about T ≳ 10⁴ K has sufficiently different combinations of density, metallicity, and photoionization rates than colder gas such that, if the hot gas were suddenly cooler, it would still cool and heat more efficiently than T ≲ 10⁴ K gas. In other words, the thermodynamics of the gas in the simulations cannot be described by a single set of a cooling plus a heating function that could be computed with common tools, such as Cloudy.

Keywords: galaxies — methods, numerical — cosmology

1. INTRODUCTION

The physics of galaxy formation depends on the interplay between gravitational compression and dissipative cooling of the proto-galactic material. On smaller scales, this same behavior is replicated in star formation (e.g. Binney 1977; Rees & Ostriker 1977; Silk 1977). For example, the cooling rate of gas in a galactic disk can affect the accretion rate of new material onto the disk, which in turn affects the star formation rate (Kannan et al. 2013).

Cooling and heating functions describe how the energy density of a gas fluid element changes with time due to radiative processes (e.g. Tucker & Gould 1966; Cox & Tucker 1969; Sutherland & Dopita 1993). Hence, these functions play an important role in galaxy formation. The form of these functions depend on the ionization states and energy levels of atoms and ions, and have been extensively calculated and tabulated for solar and cosmic abundances with the assumption that the gas is in Collisional Ionization Equilibrium (CIE). CIE assumes that there is no incident ionizing radiation and the abundances of various ions are set by a balance between collisional ionization and recombination (Cox & Tucker 1969; Sutherland & Dopita 1993; Tucker & Gould 1966). Under the assumption of CIE, the cooling and heating functions depend only on the gas temperature, density, and metallicity. Without the CIE assumption, the cooling and heating functions can depend on any physical quantity which affects the ionization states and energy levels of any chemical element in the gas. In particular, one such quantity is the incident radiation field, specified by its specific intensity Jν. Radiation fields can ionize and change the energy levels of ions, thus affecting which atomic transitions can emit or absorb photons. Previous works indicate that
the presence of ionizing radiation fields can significantly modify the cooling and heating functions of gas (e.g. Gnedin & Hollon 2012; Wiersma et al. 2009; Faerman et al. 2021; Romero et al. 2021).

Since radiation fields impact cooling and heating functions, which, in turn, impact galaxy formation, incident radiation fields can affect galaxy formation in a non-trivial way. Some examples of this include suppressing of cooling, leading to fewer dwarf galaxies forming (Éstathiou 1992) or preventing cooling of gas at $T \sim 10^{4-4.5}$ K through suppression of cooling via photoionization of neutral hydrogen (Ceverino et al. 2014).

Proper modeling of cooling and heating functions therefore requires an understanding of the dependence of cooling and heating functions on the incident radiation field $J_\nu$. For example, Wiersma et al. (2009) demonstrates that photoionization by extragalactic radiation can modify cooling functions by about an order of magnitude in realistic conditions. There are various ways to approach modeling this dependence, with varying accuracy. The most conceptually straightforward approach is to compute the cooling and heating functions using the full radiation field via a radiative transfer code such as Cloudy (Ferland et al. 1998). However, this is too computationally expensive to be viable in simulations. A more practical approach is to tabulate results from Cloudy with gas temperature, density, and metallicity assuming a spatially constant but temporally varying extragalactic background (e.g. Haardt & Madau 2001; Faucher-Giguère et al. 2009; Faucher-Giguère 2020). Both Illustris (Vogelsberger et al. 2014, 2013) and EAGLE (Schaye et al. 2014), two state of the art cosmological hydrodynamic simulations, use such an approach. While this approach does incorporate some effects of photoionizing radiation on cooling and heating, it does not account for the radiation field from local sources within galaxies, which is by far the dominant contribution (Schaye et al. 2014).

Gnedin & Hollon (2012) describe a straightforward, albeit approximate, way to incorporate local $J_\nu$ contributions by approximating the full radiation spectrum dependence with several key photoionization rates. Hence, one can tabulate the values for cooling and heating functions in a reasonably sized grid in temperature, density, metallicity, and photoionization rates. We will describe this approach in further detail in section 2.2.

In this paper, we examine the cooling and heating functions of simulated galaxies from the Cosmic Reionization on Computers (CROC) project (Gnedin 2014). In these simulations, the dependence of the cooling and heating functions on the local radiation field is computed using the approximation scheme of Gnedin & Hollon (2012). We compare two approaches to finding the median cooling and heating function across halos of similar mass at a given redshift to see whether the forms of these functions vary, and if so, how. In section 2, we discuss the methodology: the simulations we use, how we calculate the cooling and heating functions, and the two different cooling and heating function medians we consider. In section 3, we demonstrate our results comparing the cooling and heating function medians. Finally, we close with a summary and discussion of our results and potential future work in section 4.

2. METHODOLOGY

2.1. CROC Simulations

For this work, we use simulations from the Cosmic Reionization on Computers (CROC) project, a program of simulations utilizing the Adaptive Refinement Tree (ART) code (Kravtsov 1999; Kravtsov et al. 2002; Rudd et al. 2008). The simulations include many physical processes expected to be necessary to model cosmic reionization self-consistently. These processes include gravity, gas dynamics, star formation, stellar feedback, the formation of molecular hydrogen, ionizing radiation from stars and other sources, radiative transfer, and the cooling functions of hydrogen and helium computed using the approximation scheme of Gnedin & Hollon (2012). The ionizing radiation due to stars is the only ionizing radiation source fully calculated self-consistently. The simulation incorporates other sources in the radiation background as seen by all regions of the simulation, instead of calculating the contribution from those sources locally. For more details on the CROC simulations, see Gnedin (2014).

For this work, we use one $20h^{-1}$ comoving Mpc box size simulation realization (denoted box $A$), which has a spatial resolution of 100 pc. CROC resolves the radiation field in both space and time, allowing us to study both the space and time-dependence of cooling and heating functions.

2.2. Cooling and Heating Functions

We can divide the rate of change of the gas energy density due to radiative processes into two pieces: processes which increase the energy density of the gas (heating processes), and processes which decrease the energy density of the gas (cooling processes). Guided by this distinction, we can write:

$$\left. \frac{du}{dt} \right|_{\text{rad}} = n_b^2 [\Gamma(T,\ldots) - \Lambda(T,\ldots)],$$

where $u$ is the energy density of the gas, $n_b$ is the number density of baryons (here, protons and neutrons), and
\( \Gamma, \Lambda \) are the respective heating and cooling functions of the gas; \( T \) is the gas temperature and ‘\( \ldots \)’ in the cooling and heating functions indicate that these functions generally depend on additional variables besides \( T \). The factor of \( n_b^2 \) accounts for the baryon number density dependence of collisional processes involving two gas particles. In collisional ionization equilibrium (CIE), where collisional ionization is balanced by electron recombination, the prefactor of \( n_b^2 \) ensures that both \( \Gamma \) and \( \Lambda \) are independent of \( n_b \) in the absence of three-body processes (Gnedin & Hollon 2012). Note that the left-hand side of equation 1 only includes changes in energy density due to radiative processes, excluding other processes (e.g., gas heating due to adiabatic compression).

While \( \Gamma \) and \( \Lambda \) are independent of density \( n_b \) and depend only on gas temperature and metallicity for gas in CIE, an incident radiation field \( J_r \) can modify the distribution of energy levels and ionization states of gas particles, changing \( \Gamma \) and \( \Lambda \). For an arbitrary \( J_r \), calculating \( \Gamma \) and \( \Lambda \) would require a radiative transfer code such as Cloudy (Ferland et al. 1998). In order to calculate the radiation field-dependent cooling and heating functions, we use the approximation scheme of Gnedin & Hollon (2012). This is the same approximation that CROC uses to follow gas cooling and heating within the simulation, making this procedure self-consistent (Gnedin 2014).

This approximation assumes that \( J_r \) follows a general form including contributions from stars and active galactic nuclei (AGN). The implementation approximates the \( J_r \) dependence with 4 key photoionization rates: HI (neutral hydrogen), HeI (neutral helium), CVI (quintuply-ionized carbon), and the Lyman-Werner band photodissociation rate for molecular hydrogen (parameterized by \( Q_{HI}, Q_{HeI}, Q_{CVI}, \) and \( Q_{LW} \), where \( Q_i = P_i/n_b \), and \( P_i \) is the photoionization rate for the relevant band). The cooling and heating functions also depend on the local gas temperature \( T \), baryon number density \( n_b \), and metallicity \( Z \). The heating and cooling functions are computed using the radiative transfer code Cloudy for a table of 4000 values of these parameters, and linear interpolation in each parameter is used for intermediate values (Gnedin & Hollon 2012).

This approximation scheme fares well compared to Cloudy calculations within the parameter space of the table described above. When evaluated on a uniformly log-spaced grid of parameter values (different from the table described above) and compared to the cooling and heating functions calculated by Cloudy, the approximation scheme leads to fractional errors > 2 in fewer than 1 in 10^3 cases. Fractional errors of about 6 occur in around 1 in 10^6 cases (Gnedin & Hollon 2012).

### 2.3. Instantaneous vs. Flowline Averaging

We now consider how to describe the cooling and heating functions in a simulation. Resolution elements (in our case grid cells) in a simulation have a range of temperatures, densities, metallicities, and radiation fields, and hence also a range of cooling and heating rates. Here, ‘rates’ refer to the cooling and heating functions numerically evaluated for each individual grid cell using the appropriate temperature, density, metallicity, and photoionization rates. To put this question in a broader context, imagine that someone wants to simulate a set of individual galaxies similar to ones modeled in our cosmological simulations. What cooling and heating functions should they adopt?

The most straightforward approach is to simply compute the cooling and heating functions (as a function of temperature, but with fixed density, metallicity, and photoionization rates) in each resolution element and then take an average or a median. We choose to use the median, since this is less sensitive to outliers. The median describes the “typical” cooling and heating function seen by all gas elements in our simulated galaxies. In this approach, we do not use the actual temperature of the cell. Instead, each cell contributes its full cooling and heating functions to the median description,

\[
\bar{F}_i(T) = \langle F(T, n_i, Z_i, J_i(\nu)) \rangle_i ,
\]

where \( F \) is either a cooling function, \( \Lambda \), or a heating function, \( \Gamma \). Index \( i \) encapsulates cells belonging to a particular subsample of the interstellar medium, such as gas from a single galaxy, or from a population of galaxies at fixed mass. We call this median instantaneous, as it represents the cooling and heating functions at a given instant in time, affected by the thermo- and chemodynamical quantities each gas element has with their current incident radiation fields.

In the second approach we measure the actual cooling and heating rates that each cell has at a given moment. These rates depend on the cell temperature \( T_i \), so that type of average is

\[
\bar{F}_F(T) = \langle F(T, n_i, Z_i, J_i(\nu)) \rangle_{|T - T_i| < \Delta T} ,
\]

where \( \Delta T \) is a width of a temperature bin that needs to be introduced for the median to be defined. We call this median flowline, as it represents the actual cooling and heating rates seen by the cells in the simulation. This distinction is subtle but important: the instantaneous cooling and heating functions are still cooling and heating functions for some “typical” values of density \( n_i \), metallicity \( Z_i \), and the radiation field \( J_i \) (this is simply the mean value theorem):

\[
\bar{F}_i(T) = F(T, n_i, Z_i, J_i(\nu)) ,
\]
while the flowline cooling and heating functions may not (and, as we will see, do not) correspond to any physical cooling and heating function because they are really a collection of cooling and heating rates measured in a diverse set of locations. As a given gas parcel cools or heats in its environment, we may not expect gas to continue to flow along its instantaneous function if its other quantities sufficiently co-evolve to change its instantaneous description.

In order to illustrate that a collection of cooling and heating rates is not equal to the cooling and heating function, let us consider a single fluid element with the given density \( n_i \), metallicity \( Z_i \), and the radiation field \( J_i \). Its cooling function is \( \Lambda (T_i, n_i, Z_i, J_i(\nu)) \). As that fluid element cools thermodynamically (let us assume its heating function is initially small), it also evolves dynamically. So, the element’s density and possibly the radiation field change. The cooling rate along the flowline of that fluid element is \( \dot{E}_C(t) = \Lambda (T_i(t), n_i(t), Z_i(t), J_i(\nu(t))) \) and the collection of these cooling rates in some time interval, \( \{\dot{E}_C\}_{t_0 < t < t_1} \), may not correspond to any physical cooling function \( \Lambda(T_i(t), n_i, Z_i, J_i) \) for some fixed \( n_i, Z_i, \) and \( J_i \). We show in subsequent sections that this is in fact the case.

2.4. Median Cooling and Heating Functions of the Interstellar Medium

We ultimately want to examine how the flowline and instantaneous cooling and heating functions of the interstellar medium of galaxies in our cosmological simulations vary with cosmologically relevant quantities, such as redshift \( z \) and host halo mass. Before we can quantify this behavior we first need to examine differences in median cooling and heating functions to capture the average behavior of galaxies in a given mass range and at a given redshift.

In practice, we consider dark matter halos within the cosmological simulation, rather than individual galaxies. For each halo identified by the ROCKSTAR (Behroozi et al. 2012) halo catalog at the relevant redshift, we select all gas cells within one virial radius \( r_{\text{vir}} \) of the center of each halo. For the mass of the halo, we use the virial mass \( M_{\text{vir}} \) from the ROCKSTAR halo catalog. To account for potential effects due to variations in spatial clustering, we also distinguish between central halos and subhalos using the ‘parent ID’ from the ROCKSTAR halo catalog. The particular simulation from the CROC project we use for this work has redshift snapshots ranging between \( z \sim 5 \) and \( z \sim 10 \). Except for when considering the mass dependence of the cooling and heating functions, we choose a fiducial mass range of \( M_{\text{vir}} > 10^{10} h^{-1} M_\odot \) (for the rest of this paper, we write \( M \) for \( M_{\text{vir}} \), as virial masses are the only masses used here). For each combination of mass range, redshift, and choice of central or subhalos, we randomly select 50 halos when they are available, and otherwise select all the halos. To find and utilize the temperature, number density, metallicity, and photoionization rates of cells within each halo, we used the toolkit yt (Turk et al. 2011). We find the median cooling and heating function behavior in two different ways. The first way is to find the median for all of the gas cells across all halos in the mass and redshift bin, which we call the ‘all halo cells’ median. The alternative is to first find the median cooling and heating functions of gas cells in each halo, then take the median across all halos in that mass and redshift bin, which we call the ‘halo-by-halo’ median.

In general, we do not expect these two methods to yield the same results. Examining the median and quartile spread (the interval between the 25th and 75th percentiles) from each method allows us to compare two sources of spread in the cooling and heating functions. The ‘all halo cells’ and ‘halo-by-halo’ medians respectively provide information to the spread across the gas cells within each halo and the spread between the medians of each halo.

We also apply cell selection criteria when calculating the cooling and heating functions. We examine the cooling and heating functions for cells in the density range of \( 1 < n_b < 10 \text{ cm}^{-3} \) and with radiation field values \( P_{\text{HI}}, P_{\text{HeI}}, \) and \( P_{\text{CVI}} > 0 \). The density range corresponds to the typical galactic ISM. Gas cells within this density range have temperatures \( T \) spanning the entire range of \( T \) within the halo (as low as a few K), while gas cells above (up to \( \sim 10^4 \text{ cm}^{-3} \)) and below (down to \( \sim 10^{-4} \text{ cm}^{-3} \)) this density range mostly sample temperatures above \( \sim 4 \times 10^4 \text{ K} \). We apply the selection criteria for radiation fields because values outside of these ranges (i.e. any of \( P_{\text{HI}}, P_{\text{HeI}}, P_{\text{CVI}} \) equal to 0) can yield anomalously large cooling and heating function values with the approximation described in Section 2.2. The table used to interpolate between photoionization rate values in the approximation does not extend to \( P_{\text{HI}}, P_{\text{HeI}}, P_{\text{CVI}} \) this low, so we interpret these cooling and heating function values as numerical artifacts. Note, no more than a few percent of gas cells (for halos in our fiducial mass range at a given redshift) are cut from our cooling and heating function calculation with these radiation field selection criteria (after the density selection criterion has already been applied). We also discuss, in Section 3.2, the distribution of the radiation field in our simulated galaxies, and how this impacts the galactic cooling and heating functions.
Figure 1. Comparison of instantaneous (left column) and flowline (right column) medians for the cooling (top row) and heating (bottom row) functions for 50 randomly selected central halos in our fiducial mass range of $M > 10^{10} h^{-1} M_\odot$ at $z \sim 5$. Solid blue curves (shaded bands) show the median (quartile spread) of the cooling and heating functions calculated from cells across all halos (‘all halo cells’ median). The dashed orange curves (shaded bands) show the median (quartile spread) of the cooling and heating functions calculated from the median cooling and heating functions of each halo (‘halo-by-halo’ median). For consistency, we use the same random sample of 50 halos for both medians. For the instantaneous case, the quartile spread of the ‘all halo cells’ median is larger than the quartile spread of the ‘halo-by-halo’ median at all $T$, and by more at smaller $T$. For the flowline case, the quartile spreads of the two medians are comparable.

Figure 1 shows the resulting median cooling (top row) and heating (bottom row) functions for 50 randomly selected central halos at $z \sim 5$ in our fiducial mass range ($M > 10^{10} h^{-1} M_\odot$). The left panel shows the calculation for the instantaneous median, and the right for the flowline median, as described in Section 2.3. The blue solid lines show the resulting cooling and heating functions using the ‘all halo cells’ median in each temperature bin, and the orange dashed lines show the median of the medians for each halo, i.e. the ‘halo-by-halo’ median. The shaded regions enclose the respective 25th and 75th percentile values in each temperature bin. For the ‘all halo cells’ median, these are the 25th and 75th percentiles of the cooling and heating function values for all cells in the temperature bin. For the ‘halo-by-halo’ median, these are the 25th and 75th percentiles of the individual halo medians. To choose temperature bins, we begin by finding the minimum and maximum cell temperatures for the halos under consideration. We construct logarithmic temperature bins between these values, with 20 bins per decade. For ease of comparison, we evaluate the instantaneous median of the cooling and heating functions for the same halos at the logarithmic center of the bins used for the flowline median (the geometric mean of the bin edges).

From Figure 1 we see that the spread of the cooling and heating functions across all halo cells is larger than the spread across the medians for each halo, with the widest spread occurring at low temperatures for the instantaneous median of cooling and heating functions with ‘all halo cells’. This suggests that the variation of the cooling and heating functions within individual halos...
is larger than the variation between halos (at constant redshift and in the same mass bin). For the remainder of this paper, use the ‘all halo cells’ median since it better captures the spread between individual gas cells (which is essentially missed in the ‘halo-by-halo’ median).

3. RESULTS

3.1. Instantaneous vs. Flowline Behavior

We first compare the behavior of instantaneous and flowline cooling and heating functions for 50 randomly selected central halos at $z \sim 5$ in our fiducial mass range, shown in Figure 2. From Figure 2, we see that the instantaneous and flowline cooling and heating functions differ by more than the 25th-75th percentile spread below $T \sim 10^3$ K. The heating functions even have different qualitative shapes at these lower temperatures. Above $T \sim 10^4$ K, there is quantitative agreement for the cooling functions, but only qualitative agreement between the shapes of the heating functions.

The instantaneous and flowline medians are not the same for either the cooling or heating functions. This suggests that the actual cooling and heating rates experienced by actual gas cells as their temperature changes are not given by the instantaneous cooling and heating functions. Hence, we find that the flowline cooling and heating functions are not expressible in the form $F(T, n_e, Z_e, J_e(\nu))$ for fixed $n_e, Z_e, J_e(\nu)$ (as explained in section 2.3). For example, the flowline heating function is not monotonically decreasing, as all $\Gamma(T, n_e, Z_e, J_e(\nu))$ are. Since the flowline cooling and heating functions explicitly describe the thermal evolution of gas cells, we conclude that the thermodynamics of the simulated gas cells cannot be well-described by a single set of cooling and heating functions of the form $F(T, n_e, Z_e, J_e(\nu))$.

From Figure 2, we see that the instantaneous cooling and heating functions are larger than the flowline curves at low $T$ ($T \lesssim 10^4$ K), and similar or smaller at high $T$ ($T \gtrsim 10^4$ K). Since the flowline medians consider only cells within the relevant temperature bin, while the instantaneous medians utilize all cells, we see that high $T$ cells tend to increase the instantaneous cooling and heating functions at low $T$, while low $T$ cells tend to decrease the instantaneous cooling and heating functions at high $T$ (compared to the flowline cooling and heating functions). That is: if high $T$ cells were suddenly cooled to low $T$ with no other dynamical changes, they would cool and heat more efficiently than cells naturally at the same low $T$ value. Similarly, if low $T$ cells were suddenly heated to a high $T$ value with but were otherwise unchanged, they would cool and heat less efficiently than cells naturally at the same high $T$ value. This implies that the ‘dynamical’ effects of the change in a gas cell’s environment as it cools (or heats) will impact the evolution of gas cooling and heating functions.

3.2. Bimodality in $P_{CVI}$

The distribution of cooling and heating rates at low temperatures ($T \lesssim 10^4$ K) can be very broad, spanning several orders of magnitude due to wide variations in the

Figure 2. Comparison of instantaneous (solid orange curves) and flowline (dashed blue curves) cooling and heating functions for 50 randomly selected central halos at $z \sim 5$ in the fiducial mass range $M > 10^{10} h^{-1} M_\odot$ (the same as shown in Fig. 1). The shaded bands show the 25th-75th percentile spread.

Figure 3. Flowline cooling and heating functions for cells in our 50 randomly selected central halos in the fiducial mass range for both the low (blue) and high (orange) values of $P_{CVI}$ at $z \sim 5$ (solid lines) and 8 (dashed lines). The darker shaded regions show the 25th to 75th percentile spread, and the lighter shaded regions show the 1st to 99th percentile spread for the $z \sim 5$ flowline cooling and heating functions. The two modes are clearly distinct for temperatures below $\sim 10^4$ K, but overlap at higher $T$. 
Figure 4. Histograms of the CVI photoionization rate $P_{CVI}$ vs the Lyman-Werner band photodissociation rate $P_{LW}$ (left) or the HI photoionization rate $P_{HI}$ (right) for cells in the 50 randomly selected central halos in the fiducial mass range at $z \sim 5$. The dashed green horizontal line shows the cutoff between the low and high radiation field parts of the distribution ($P_{CVI} = 2 \times 10^{-20} \text{ s}^{-1}$). The two populations of cells are distinguished by color. The correlation between $P_{CVI}$ and $P_{LW}$ for the low $P_{CVI}$ population has no obvious physical reason and is likely to be a numerical artifact.

The $P_{CVI}$ and $P_{LW}$ distributions correspond to the two cooling and heating function modes seen in Figure 3. A cutoff of $2 \times 10^{-20} \text{ s}^{-1}$ (as shown in the mid-plot horizontal axis in Figure 4) separates the two modes at all the redshifts we examined. The range of $P_{CVI}$ for the low $P_{CVI}$ distribution does not vary strongly with redshift. However, the location of the narrow range of high $P_{CVI}$ values systematically increases with time from $\sim 5 \times 10^{-19} \text{ s}^{-1}$ at $z \sim 10$ to $\sim 3 \times 10^{-17} \text{ s}^{-1}$ at $z \sim 5$ as the cosmic X-ray background gradually builds up with time.

The cells in each mode are not separated in the phase space of gas properties. That is, cells in both parts of the $P_{CVI}$ distribution are similarly distributed in temperature, number density, and metallicity. This suggests that the bimodality (in both $P_{CVI}$ and the cooling and heating rates) is a spatial effect.

We find that the fraction of cells with low and high $P_{CVI}$ varies with redshift. In Table 1, we show the fraction of total gas cells in the low $P_{CVI}$ population in each of our simulation snapshots. These correspond to cells that meet the number density and radiation field cuts described above in central halos within our fiducial mass range. While the values vary by a factor of $\sim 2$ over this redshift range, they do not exhibit a systematic trend with redshift.

### Table 1. Redshift evolution of low $P_{CVI}$ cell fraction

<table>
<thead>
<tr>
<th>Redshift $z$</th>
<th>Fraction of low $P_{CVI}$ cells (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.9</td>
</tr>
<tr>
<td>8</td>
<td>6.8</td>
</tr>
<tr>
<td>9</td>
<td>3.4</td>
</tr>
<tr>
<td>10</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The $P_{CVI}$ distribution correspond to the two cooling and heating function modes discussed in section 3.2 do not combine in a trivial way for the instantaneous case. We include cells from both of the $P_{CVI}$ modes when calculating instantaneous cooling and heating functions (although the high $P_{CVI}$ cells will dominate since there are many more of them at all redshifts, as shown in Table 1). Figure 5 shows the instantaneous cooling and heating functions for gas in central halos in our fiducial mass range at $z \sim 5, 8, 9$, and 10 in the solid curves. For comparison, the dashed

number density, metallicity, and the 4 photoionization rates in such gas cells. However, the distribution of cooling and heating rates at fixed temperature is not continuous across the entire range, but rather is bimodal. Figure 3 shows the flowline cooling and heating functions for the two ‘modes’, which we call ‘low $P_{CVI}$’ and ‘high $P_{CVI}$’ at redshifts $z \sim 5$ and $z \sim 8$. We will discuss the meaning of these modes below. The two modes have very similar flowline cooling and heating functions above $T \sim 10^4 \text{ K}$, but the cooling and heating functions of the low $P_{CVI}$ mode are systematically higher at lower temperatures. At $z \sim 10$, these two modes are not distinguishable because the halos at this redshift do not contain any cells at the lower temperatures where the bimodality occurs.

What drives this bimodality in the cooling and heating functions? It turns out that the distribution of the CVI photoionization rate, $P_{CVI}$, of gas cells in all galaxies in the fiducial mass range is also distinctly bimodal across the entire range of simulated redshifts, with no difference in behavior between galaxies hosted by central or subhalos. A representative plot is shown for our 50 randomly selected central halos at $z \sim 5$ with masses $M > 10^{10} h^{-1} M_\odot$ in Figure 4. We term the two distinct regions of the distribution ‘low $P_{CVI}$’ for gas populating the distribution in blue and ‘high $P_{CVI}$’ for gas populating the distribution in orange. These parts of

3.3. Redshift Trends

Neither the cooling and heating rates for cells in the low and high $P_{CVI}$ modes, nor the fraction of cells in each mode, vary strongly with redshift. This suggests that the flowline cooling and heating functions should also not display any strong trends with $z$. The instantaneous cooling and heating functions are independent of the temperature distribution of gas cells. Therefore, the two modes discussed in section 3.2 do not combine in a trivial way for the instantaneous case. We include cells from both of the $P_{CVI}$ modes when calculating instantaneous cooling and heating functions (although the high $P_{CVI}$ cells will dominate since there are many more of them at all redshifts, as shown in Table 1). Figure 5 shows the instantaneous cooling and heating functions for gas in central halos in our fiducial mass range at $z \sim 5, 8, 9$, and 10 in the solid curves. For comparison, the dashed
Figure 5. Instantaneous cooling and heating functions vs. temperature for up to 50 central halos in the fiducial mass range at $z = 5, 8, 9, 10$ (solid lines) and for sub halos at $z \sim 5$ (dashed lines). The solid lines show the median, while the shaded bands show the 25th-75th percentile spread for central halos at $z \sim 5$. At $z \sim 10$, the median cooling and heating functions are about two orders of magnitude larger than at lower redshifts, reflecting the weakness of the radiation fields in the earliest galaxies. The cooling and heating functions for central and subhalos agree to within the quartile spread at $z \sim 5$. Note that the temperature range for each curve is given by the minimum and maximum temperatures of the selected (i.e. within the density and photoionization rate ranges we require) cells in the up to 50 halos used at the given redshift.

Lines correspond to the same curves for gas in subhalos at $z \sim 5$.

From Figure 5, we see that there is no evolution of the instantaneous cooling and heating functions with redshift for $5 \lesssim z \lesssim 8$, but that the the cooling and heating functions increase with increasing $z$ at low temperatures for $8 \lesssim z \lesssim 10$. We see similar results for subhalos, with the exception that subhalos in our fiducial mass range only exist for $z \lesssim 8$. As seen in Figure 5, the instantaneous cooling and heating functions for subhalos and central halos at $z \sim 5$ are indistinguishable to within the 25th-75th percentile spread. We conclude that there is no evolution in the instantaneous cooling or heating function between $5 \lesssim z \lesssim 8$.

As discussed in section 3.1, the instantaneous cooling and heating functions at low temperature are driven to be larger than the flowline functions due to the contribution of cells with high $T$. However, the strength of this effect varies with redshift since the fraction of cells colder than a cutoff temperature $T_c$ is a function of redshift. It turns out that the fraction of cells colder than $10^4$ K has little redshift dependence. The redshift dependence of the cell fraction colder than a cutoff temperature $T_c$ vs. $T_c$ is shown in Figure 6. At $T_c \sim 10^3$ K, the fraction of colder cells (with $T < T_c$) increases with decreasing redshift. That is, as redshift increases there are more cells with $T > T_c$. Since it is these cells which increase the instantaneous cooling and heating functions at low $T$, this increase should be larger at higher redshift, as we observe in Figure 5. Furthermore, Figure 6 shows little difference between $z \sim 5$ and $z \sim 8$ (except at the smallest temperatures $T \sim 10$ K), while the $z \sim 9$ and $z \sim 10$ curves clearly differ from each other and the $z \sim 5, 8$ curves for $T \gtrsim 2 \times 10^5$ K. This suggests a possible explanation for why Figure 5 shows no redshift evolution for $5 \lesssim z \lesssim 8$, and instantaneous cooling and heating functions which increase with $z$ at low $T$ for $8 \lesssim z \lesssim 10$. At high redshift $8 \lesssim z \lesssim 10$, the distribution of cell temperatures evolves significantly, with more gas cells at high temperatures. However, once we reach $z \sim 8$, the cell temperature distribution does not significantly evolve.

3.4. Mass dependence

To justify our choice of a wide fiducial halo mass range $M > 10^{10} h^{-1} M_\odot$ in the previous sections, we examine the flowline and instantaneous cooling and heating functions in narrow mass bins across the range of halo masses at $z \sim 5$. We choose mass bins with ratio 1.1 with left edges at $10^{10}, 5 \times 10^{10}$, and $10^{11} h^{-1} M_\odot$.

As explained in section 3.2, the flowline cooling and heating functions have two modes corresponding to two populations of $P_{CV1}$ values. We therefore examine the mass dependence of both modes separately, along with the instantaneous cooling and heating functions (which includes cells in both $P_{CV1}$ modes). We show the cooling
and heating functions in different mass bins at $z \sim 5$ in Figure 7. From this, we see that the distribution of cooling and heating rates (the two flowline curves) is bimodal at fixed $T$ for $T \lesssim 3 \times 10^4$ K for all masses. We also observe that neither mode varies strongly with the halo mass. Additionally, we observe no halo mass dependence for the instantaneous cooling and heating functions at $z \sim 5$, shown in the green line and band in Figure 7, corresponding to the median and quartile spread for the functions. While there are slight offsets in the curves for the three mass bins at low $T$ ($\lesssim 10^5$ K for heating and $\lesssim 10$ K for cooling), these offsets are much smaller than the 25th-75th percentile bands. We conclude that the instantaneous cooling and heating functions do not depend on the halo mass within our fiducial mass range.

4. SUMMARY AND DISCUSSION

In this work, we compare the instantaneous and flowline cooling and heating functions of halos in a simulation from the CROC project to assess the validity of universal (i.e. independent of redshift and halo mass) cooling and heating function formulations. The main conclusions from this work are:

- The flowline cooling and heating functions, which correspond to the actual gas thermodynamics, cannot be described by the canonical cooling and heating functions of temperature for any values of gas density, metallicity, or the radiation field. While one can still parameterize these functions as functions of temperature, such parameterizations are “unphysical” in a sense that they cannot be computed by, say, Cloudy, with some fixed values of the gas density, metallicity, and the radiation field. In particular, the flowline heating function exhibits non-monotonic dependence on temperature.

- Differences between the density, metallicity, and incident radiation fields of hot ($T \gtrsim 10^4$ K) and cold ($T \lesssim 10^4$ K) gas mean that if hot gas were suddenly cooled to $T \lesssim 10^4$ K, it would cool and heat more efficiently than the actual gas at these temperatures. Similarly, if cold gas were suddenly heated to $T \gtrsim 10^4$ K, it would cool and heat less efficiently than the actual gas at these temperatures. Thus, the ‘dynamic’ change in a cell’s environment as it heats or cools impacts the gas cooling and heating functions. Especially important for the overall gas dynamics is the comparison between the dynamical time scale (describing how long it takes perturbations to cross the gas cloud) and the cooling time scale (describing how long it takes the gas to radiate away energy). The large observed difference between instantaneous and flow cooling and heating functions imply that dynamical times are not much longer than cooling and heating times in the modeled galaxies.

- The cooling and heating rates exhibit a bimodality at fixed temperature for cool gas at $T \lesssim 10^4$ K (see Figure 3). A population of locations with low carbon VI photoionization rates, $P_{CVI}$, drives the behavior.

- There is no significant redshift evolution either for the flowline cooling and heating functions, or for the instantaneous case between redshifts $5 \lesssim z \lesssim 8$. However, the instantaneous cooling and heating functions for $T \lesssim 10^4$ K increase with redshift between redshift $8 \lesssim z \lesssim 10$ (see Figure 5), reflecting the weakness of the radiation fields and the lower mass fraction of the cold ISM in the earliest galaxies.

- We observed no systematic difference between the flowline or instantaneous cooling and heating functions of central and subhalos, indicating no significant dependence due to spatial clustering.
• There is no significant mass trend in either the flowline or instantaneous cooling and heating functions across a decade of mass within our fiducial mass bin (see Figure 7).

• The scatter in cooling and heating rates is dominated by the scatter within individual halos rather than the scatter between different halos (see Figure 1).

The impact of the bimodal $P_{CVI}$ values on cooling and heating functions illustrates the importance of accounting for the various contributions to the radiation field. The bimodality does not have a clear spatial dependence or gas phase dependence. Accounting for that effect requires more detailed numerical simulations with at least approximate modeling of the spatially inhomogeneous radiation field.

The correlation between $P_{CVI}$ and $P_{LW}$ for the low $P_{CVI}$ population seen in Figure 4 is surprising. CVI is ionized by X-rays, sourced only by the spatially constant quasar background in the simulation. On the other hand, the UV radiation in the Lyman-Werner (LW) bands comes from both local stellar sources and a spatially constant UV background (Gnedin 2014). Since these rates originate from disparate sources, there is no obvious reason why they should be correlated. Hence, we interpret the observed correlation in the values of $P_{CVI}$ and $P_{LW}$ rates as a previously unidentified numerical artifact of the radiative transfer solver.

Another discovered numerical artifact is related to the anomalously high cooling and heating function values in cells with $P_{HI}$, $P_{HeI}$, or $P_{CVI} = 0$. That artifact can be eliminated by extending the interpolation tables in the approximation of Gnedin & Hollon (2012) to smaller values of $P_{HI}$, $P_{HeI}$, and $P_{CVI}$. In addition to extending the interpolation tables, it may also be possible to improve the approximation (and extend its range of validity further) by using a different combination of photoionization rates. Machine learning provides a promising tool to assess what photoionization rates most impact cooling and heating functions. In a future project, we can use these rates to construct new interpolation tables.

Finally, another feature of our dataset to note is that the halos in our fiducial mass range have only a few cells with low $T$ and low $P_{CVI}$, as indicated by the sparsity of populated bins for the low $P_{CVI}$ curves in Figure 3. Previous work has indicated that CROC simulations underpredict the star formation rates for the highest mass ($\sim 10^{11} M_{\odot}$) halos (Zhu et al. 2020). This suggests that these halos have anomalously enhanced feedback (suppressing star formation), which naturally leads to fewer cells at low temperature. A future study could investigate whether the lack of gas at low $T$ in the low $P_{CVI}$ population is solely attributable to overpredicted stellar feedback, or if it has other causes.
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