A Model-independent Indicator for the Speed of Cosmic Reionization

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The antisymmetric part of two-point cross-correlation between intensity maps of the HI 21 cm line and the CO 2.61 mm line has emerged as a new probe of cosmic reionization. In this Letter we demonstrate that the slope of the dipole of HI-CO cross-power spectrum at large scales is linear to the rate of change of global neutral fraction of hydrogen in a model-independent way, until the slope levels out near the end of reionization. The HI-CO dipole, therefore, can be a smoking-gun probe for the speed of reionization, or “standard speedometer”. Observations of this new signal will unveil the global reionization history from the midpoint to near the completion of reionization.

In a companion Letter, we proposed a new intensity mapping analysis method, the antisymmetric cross-correlation between the HI 21 cm line and the CO 2.61 mm line intensity maps from the epoch of reionization (EOR). From the observational point of view, the most interesting advantage of this new analysis is that this signal is unbiased by foregrounds and thus can be measured directly from the foreground-contaminated data. It arises because the statistical fluctuations of the 21 cm field have much more rapid evolution in time than the CO(1-0) line field, and therefore the HI-CO antisymmetric cross-correlation contains additional information of the progressing of cosmic reionization, complementary to the symmetric component of cross-correlation. For example, in the companion Letter we show that the sign of this signal can generically tell whether inside-out reionization happens during some time interval, regardless of the detail of reionization model.

How the HI-CO antisymmetric cross-correlation, as a new probe of cosmic reionization, depends on reionization models calls for thorough investigations. As an attempt in this regard, we focused on a special reionization model and showed that the HI-CO antisymmetric cross-correlation can improve the constraint on the model parameters significantly. Instead, this Letter is devoted to investigate the generic feature regarding model dependence and independence.

Simulations.—We perform semi-numerical simulations of reionization with the publicly available code 21cmFAST[2,3]. This code quickly generates the fields of density, velocity, ionized fraction, spin temperature and 21 cm brightness temperature on a grid. It is based on the semi-numerical treatment of cosmic reionization with the excursion-set approach[4] to identify ionized regions. Specifically, cells inside a spherical region are identified as ionized, if the number of ionizing photons in that region is larger than that of neutral hydrogen atoms. Our simulations were performed on a cubic box of 768 comoving Mpc on each side, with 512^3 grid cells. Our EOR model is parameterized with three parameters: ζ (the ionizing efficiency), T_{\text{vir}} (the minimum virial temperature of halos that host ionizing sources), and R_{\text{mfp}} (the mean free path of ionizing photons). For the purpose of illustration, we choose a reference case with the parameter values ζ = 25, T_{\text{vir}} = 3 \times 10^4 K, R_{\text{mfp}} = 50 \text{Mpc}. This yields a global reionization history in which the reionization starts at z \approx 16 and ends at z \approx 6.5, with the cosmic microwave background (CMB) Thomson scattering optical depth τ = 0.068, consistent with current observational constraints on the reionization history[5]. To shed light on the nature of the HI-CO dipole, we further consider a wider range of astrophysical parameters in the EOR model as listed in the legend of Fig. 1. In all cases, R_{\text{mfp}} = 50 \text{Mpc} is fixed because the results depend on this parameter very weakly. Fig. 1 shows that these models result in very different reionization histories as well as different rates of change of mean neutral fraction, d\delta_{\text{HI}}/dz, or the “speed” of reionization.

In this Letter, we adopt the standard ΛCDM cosmology with fixed values of cosmological parameters based on the Planck 2016 results[6], (h, Ω_m, Ω_\Lambda, σ_8, n_s) = (0.678, 0.306, 0.0492, 0.694, 0.82, 0.968).

Modelling the brightness temperature.—The 21 cm brightness temperature at position x relative to the CMB temperature can be written[7] as

\[ T_{21}(x, z) = T_{\text{21}}(z) x_{\text{HI}}(x) [1 + \delta(x)] \left( 1 - \frac{T_{\text{CMB}}}{T_S} \right), \]

where \( T_{\text{21}}(z) = 27 \sqrt{[(1+z)/10](0.15/\Omega_m h^2)(\Omega_b h^2/0.023)} \) in units of mK. Here, \( x_{\text{HI}}(x) \) is the neutral fraction, and \( \delta(x) \) is the matter overdensity, at position x. We assume the baryon distribution traces the cold dark matter on large scales, so \( \delta_{\text{PH}} = \delta \). In this Letter, we focus on the limit where spin temperature \( T_S \gg T_{\text{CMB}} \), valid soon after reionization begins. As such, we can neglect the dependence on spin temperature. Also, for simplicity, we ignore the effect of peculiar velocity, because it only weakly affects the light-cone effect.

The CO(1-0) line specific intensity can be written[8] as

\[ I_{\text{CO}}(x, z) = I_{\text{CO}}(z) [1 + b_{\text{CO}}(z) \delta(x)] \]

with the mean intensity \( I_{\text{CO}}(z) \) and the bias \( b_{\text{CO}}(z) \) at redshift z. The equivalent brightness temperature is computed using the
Rayleigh-Jeans Law, \( T_{\text{CO}} = c^2 I_{\text{CO}}/(2 k_B \nu_{\text{obs}}^2) \). Therefore, it can be written as
\[
T_{\text{CO}}(x, z) = \bar{T}_{\text{CO}}(z) \left[ 1 + b_{\text{CO}}(z) \delta(x) \right]. \tag{2}
\]
Here the observed frequency \( \nu_{\text{obs}} = \nu_{\text{CO}}/(1 + z) \) for gas at redshift \( z \) emitting in the CO(1-0) line with the restframe \( \nu_{\text{CO}} = c/\lambda_{\text{CO}} = 115 \text{ GHz} \) and \( \lambda_{\text{CO}} = 2.61 \text{ mm} \).

The mean intensity [8, 9] is \( \bar{I}_{\text{CO}}(z) = (\lambda_{\text{CO}}/4 \pi H(z)) \int_{M_{\text{CO, min}}}^{\infty} dM \left( \frac{dn}{dM}(M, z) L_{\text{CO}}(M) \right) \), where \( dn/dM \) is the halo mass function [10] and \( L_{\text{CO}}(M) \) is the CO(1-0) luminosity which is assumed to be a function of the halo mass \( M \). We follow the modelling of [9] in which the CO luminosity is linear to halo mass, \( L_{\text{CO}}(M) = 2.8 \times 10^{10} L_\odot (M/10^8 M_\odot) \). Under this assumption, the mean brightness temperature is [9]
\[
\bar{T}_{\text{CO}}(z) = 59.4 \mu K (1 + z)^{1/2} f_{\text{coll}}(M_{\text{CO, min}}; z), \tag{3}
\]
where \( f_{\text{coll}}(M_{\text{CO, min}}; z) \) is the mean collapse fraction at \( z \) with the lower mass cutoff at \( M_{\text{CO, min}} \). We assume that \( M_{\text{CO, min}} \), the minimum mass of halos that can host galaxies, is the same as the mass scale of atomic hydrogen cooling. In other words, \( M_{\text{CO, min}} \) corresponds to \( T_{\text{vir}} \), the minimum virial temperature of halos that can host ionizing sources.

The bias \( b_{\text{CO}}(z) \) describes how well the CO brightness temperature fluctuations trace the matter density fluctuations. It can be modelled [8, 9] as
\[
b_{\text{CO}}(z) = \frac{\int_{M_{\text{CO, min}}}^{\infty} dM \left( \frac{dn}{dM}(M, z) L_{\text{CO}}(M) b(M, z) \right)}{\int_{M_{\text{CO, min}}}^{\infty} dM \left( \frac{dn}{dM}(M, z) L_{\text{CO}}(M) \right)},
\]
where \( b(M, z) \) is the halo bias [10]. The linear luminosity assumption can further simplify this expression. Instead of evaluation by direct numerical integration, we find an analytic form for the bias \( b_{\text{CO}}(z) \). We take the form of halo bias, \( b(M, z) = 1 + (\nu - 1)/\delta_\text{c}(z) \), where \( \nu = \delta_\text{c}^2/\sigma^2(M) \), by setting \( a = 1 \) and \( p = 0 \) in equation (12) of [10]. In this case, the mass function is the Press-Schechter form. Thus we can obtain an analytical form,
\[
b_{\text{CO}}(z) = 1 - \frac{1}{\delta_\text{c}(z)} + \frac{2}{\sqrt{\pi} \delta_\text{c}(z) f_{\text{coll}}(M_{\text{CO, min}}; z)} \times \Gamma_{\text{inc}} \left( 1.5, \frac{\delta_\text{c}^2(z)}{2\sigma^2} \right), \tag{4}
\]
where the incomplete Gamma function \( \Gamma_{\text{inc}}(a, x) = \int_0^x t^{a-1}e^{-t}dt \), and \( \sigma_{\text{min}} \equiv \sigma(M_{\text{CO, min}}) \). In Fig. 2, we find that the CO bias decreases with time, a trend also found in [8].

Results.— We postprocess the reionization simulations with the method described in detail in the companion

![FIG. 1. Global reionization history for different reionization models as marked in the legend: (top) mean neutral fraction \( \bar{x}_\text{HI} \) vs redshift \( z \), and (bottom) its redshift derivative \( dx_{\text{HI}}/dz \) vs \( z \). Generically, reionization has two stages, the acceleration (“accel.”) and deceleration (“decel.”) stages.](image1)

![FIG. 2. Evolution of the CO bias. We show the CO bias \( b_{\text{CO}} \) vs redshift \( z \) in our fiducial EOR model.](image2)

![FIG. 3. The dipole of the HI-CO cross-power spectrum \( P^A \) vs wavenumber \( k \) for different reionization models (as marked in the legend of Fig. 1) at the fixed redshift \( z = 8.48 \) (corresponding to \( \bar{x}_{\text{HI}} = 0.50 \) in our fiducial model). The error bars are 1\sigma standard deviation for cosmic variance corresponding to the simulation volume of 100 realizations.](image3)
Letter, and extract the dipole, $P_A(k)$, of the cross-power spectrum between the 21 cm and CO(1-0) line brightness temperature maps. Fig. 3 shows that the HI-CO dipole at the fixed redshift of bandwidth center is very model-dependent. Thus one might use this model-dependence as the basis of constraining reionization model parameters with the HI-CO dipole.

Fig. 4 shows that the progressing of reionization generally undergoes an acceleration stage ($d^2 \bar{x}_{HI}/dz^2 < 0$) and a deceleration stage ($d^2 \bar{x}_{HI}/dz^2 > 0$). Although the dipole is model-dependent at a fixed $z$, if we compare the dipole for different reionization models at the same speed $d\bar{x}_{HI}/dz = 0.378/0.246$ of bandwidth center in the acceleration stage, which correspond to $\bar{x}_{HI} = 0.25/0.50$ in our fiducial model, respectively, we find in Fig. 4 that the dipoles for different models agree with each other, with the scatter within 1σ cosmic variance corresponding to the simulation volume of 100 realizations. We find the similar model-independence in the deceleration stage, too. This implies that the HI-CO dipole is to leading order determined by the speed of cosmic reionization $d\bar{x}_{HI}/dz$ of the bandwidth center, regardless of the detail of reionization models. This can be understood because the HI-CO dipole is dominated by the evolution effect due to cosmic reionization, which is characterized by the difference of ionization level between the front- and back-end on the lightcone, or $d\bar{x}_{HI}/dz$ to leading order.

At each fixed $d\bar{x}_{HI}/dz$ (during either acceleration or deceleration stage), we fit the HI-CO dipole of all models to a modified power law, $P_A(k) = -A_R(k/k_*)^{-n_R} \exp \left[-\beta_R(k/k_*)^{\alpha_R}\right]$,

with best-fit coefficients listed in Table I. The coefficients
TABLE I. Best-fit coefficients of the HI-CO dipole to the ansatz $P^A(k) = -A_R(k/k_*)^{-n_R}$ $\exp[-\beta_R(k/k_*)^{n_R}]$, at the fixed speed $d\bar{x}_{HI}/dz$ for the acceleration stage ("accel.") and deceleration stage ("decel.") stage, respectively. We show the slope measured for the range of $k = 0.14 - 0.27$ h Mpc$^{-1}$. Here we choose $k_* = 1$ h Mpc$^{-1}$.

|          | $d\bar{x}_{HI}/dz$ | $A_R([\mu K]^2 h^{-3} \text{Mpc}^3]$ | $n_R$ | $\beta_R$ | $\alpha_R$ | $R^2$ |
|----------|---------------------|----------------------------------------|-------|-----------|-----------|-------|
| accel.   | 0.378               | $(2.539 \pm 0.809) \times 10^6$       | 3.018 | $3.295 \pm 0.976$ | $2.790 \pm 0.430$ | 0.9898 |
|          | 0.312               | $(1.163 \pm 0.210) \times 10^6$       | 2.459 | $3.877 \pm 1.084$ | $2.433 \pm 0.391$ | 0.9734 |
|          | 0.246               | $(6.028 \pm 4.584) \times 10^5$       | 1.668 | $5.083 \pm 1.298$ | $2.513 \pm 0.368$ | 0.9542 |
| decel.   | 0.378               | $(1.849 \pm 0.624) \times 10^6$       | 3.298 | $3.557 \pm 1.738$ | $3.266 \pm 0.725$ | 0.9861 |
|          | 0.312               | $(1.842 \pm 0.588) \times 10^5$       | 3.273 | $3.212 \pm 1.189$ | $2.870 \pm 0.533$ | 0.9882 |
|          | 0.246               | $(1.530 \pm 0.700) \times 10^5$       | 3.334 | $2.729 \pm 1.152$ | $2.665 \pm 0.599$ | 0.9827 |

FIG. 5. The slope of HI-CO dipole $n_R$ vs the speed of reionization $d\bar{x}_{HI}/dz$ during the acceleration (left) and deceleration (right) stage, respectively. We show the slope measured for $k = 0.14 - 0.27$ h Mpc$^{-1}$ (black solid dots) and for $k = 0.20 - 0.40$ h Mpc$^{-1}$ (red open dots). We fit the data to a linear relation (dashed lines) in the acceleration stage and a constant (dashed lines with the shaded regions representing the 1σ error) in the deceleration stage. The arrows show the direction of time flow or increasing the redshift $z$.

$A_R$ and $n_R$ quantify the power law at large scales, while $\beta_R$ and $\alpha_R$ quantify the exponential suppression at small scales. We find that among these four coefficients, $n_R$ has the smallest error bars ($\lesssim 15\%$ in most cases) in fitting all model data, which indicates that the slope at large scales is most robust against the variation of models.

Fig. 5 shows that the slope of HI-CO dipole increases with the speed $d\bar{x}_{HI}/dz$ with an approximately linear relation, $n_R = a_1 (d\bar{x}_{HI}/dz) + a_2$, until $n_R$ reaches a maximum and levels out near the end of reionization. The linear relation can be explained by the fact that the larger speed $d\bar{x}_{HI}/dz$ can result in larger magnitude of dipole at large scales while having less effect at small scales, which makes the HI-CO dipole steeper in $k$ and increases the slope $n_R$. On the other hand, if the slope is measured for a smaller scale, then Fig. 5 shows that the slope reaches the maximum at earlier time. (We define this moment to be when $n_R$ overlaps with the 1σ region of the constant $n_R$ in the deceleration stage.) This implies that the slope reaches the maximum when the scale for which the slope is measured is below the characteristic scale of HII regions; thereafter the changes in the speed of reionization, which mostly affect the dipole on scales above the characteristic scale of HII regions, do not considerably affect the scale-dependence of the dipole on scales beneath.

Discussions.— The linear relation between the slope of HI-CO dipole at large scales and the speed of reionization can be exploited to infer $d\bar{x}_{HI}/dz$ from the $n_R$ measurement in a model-independent way. In this sense, the HI-CO dipole is a smoking-gun probe for the speed of reionization, so we term it a “standard speedometer” for cosmic reionization. However, this approach is only valid before $n_R$ levels out at the time that depends on the scale of interest. For example, if the range of scale $k = 0.14 - 0.27$ h Mpc$^{-1}$ is considered, then the effective range for standard speedometer is $0.25 \lesssim \bar{x}_{HI} \lesssim 0.52$ for all models considered herein. The upper-bound is because at even earlier time, the dipole is too small to be distinguished from the cosmic variance.

Standard speedometer is of important astrophysical application — the global reionization history $\bar{x}_{HI}(z)$, however relative to the value when the slope just begins to level out, can be reconstructed by integration of $d\bar{x}_{HI}/dz$. This approach of global history reconstruction is model-independent and unbiased by foregrounds. Measurements of the HI-CO dipole will motivate the greater synergy between 21 cm observations using radio interferometers, e.g. the low frequency array of the Square Kilometre Array (SKA), and CO observations using single dish arrays, e.g. the middle frequency array of SKA or the update of the CO Mapping Array Pathfinder (COMAP).

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