Molecular Emission from a Galaxy Associated with a \( z \sim 2.2 \) Damped Ly\( \alpha \) Absorber

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Abstract

Using the Atacama Large Millimeter/submillimeter Array, we have detected CO(3–2) line and far-infrared continuum emission from a galaxy associated with a high-metallicity ([M/H] = −0.27) damped Ly\( \alpha \) absorber (DLA) at \( z_{\text{DLA}} = 2.19289 \). The galaxy is located 3.75 kpc away from the quasar sightline, corresponding to a large impact parameter of 30 kpc at the DLA redshift. We use archival Very Large Telescope-SINFONI data to detect H\( _{\alpha} \) emission from the associated galaxy, and find that the object is dusty, with a dust-corrected star formation rate of 110\( \pm 20 \) M\( \odot \) yr\(^{-1} \). The galaxy’s molecular mass is large, \( M_{\text{mol}} = (2.5 \pm 1.2) \times 10^{11} (\alpha_{\odot}/4.3) (0.57/r_{31}) \) M\( \odot \), supporting the hypothesis that high-metallicity DLAs arise predominantly near massive galaxies.

Using the Atacama Large Millimeter/submillimeter Array (ALMA) provides a complementary approach, whereby we can search for longer-wavelength emission (e.g., from CO, [C II] lines, and radio continuum), which is less affected by the presence of dust and arises predominantly from the molecular and atomic gas inside the galaxy.

In Neeleman et al. (2016), we presented the first detection of molecular emission from a galaxy associated with a Ly\( \alpha \) absorber. In subsequent work, we found that molecular emission is detected in a large fraction of galaxies associated with high-metallicity absorbers at \( z \approx 0.7 \), and that their gas fraction is significantly higher than that of emission-selected galaxies at these redshifts (Kanekar et al. 2018, Møller et al. 2018). Encouraged by these results, we have targeted three DLAs at \( z \sim 2 \) with ALMA to search for CO emission from galaxies associated with the absorbers. One of them—the DLA toward QSO B1228–113 (Ellison et al. 2001)—is the focus of this Letter; the remaining two systems will be discussed in a future paper. Throughout this Letter we assume a standard flat Lambda Cold Dark Matter cosmology with \( \Omega_\Lambda = 0.7 \) and \( H_0 = 70 \) km s\(^{-1} \).
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Figure 1. Selection of absorption lines in the VLT-UVES spectrum. The median model (black line) and 1σ uncertainties (gray region) from the MCMC fitting routine as well as individual metal lines are shown. The vertical (gray) dashed lines mark the six velocity components of the C I, Zn II, and Ni II metal lines. The yellow lines in the top two panels are absorption features due to higher redshift intervening H I systems. The velocity offsets for Mg I and Cr II are 50 and −63 km s\(^{-1}\), respectively. Note the lack of C I absorption in the strongest Zn II and Ni II component at \(v \approx 3 \) km s\(^{-1}\).

2. Observations

2.1. UVES Observations

To search for metal lines from the DLA, a high-resolution spectrum was obtained of QSO B1228–113 using the Ultraviolet and Visual Echelle Spectrograph (UVES; Dekker et al. 2000) on the Very Large Telescope (VLT). Details of the observations and reduction procedures are described in Akerman et al. (2005). By fitting a single component to the Zn II absorption line, these authors reported a metallicity of \([\text{M/H}] = -0.22\). To provide an updated measure of the metallicity, we have renormalized the spectrum, and refitted the metal lines using a Monte Carlo Markov Chain Voigt profile fitting routine publicly available in the LINETOOLS\(^8\) package (Prochaska et al. 2017).

Specifically, we fit the Ni II λ1741 and Ni II λ1751 lines with six absorption components to provide an accurate model of the absorption profile. We then tie the component structure of the blended lines (i.e., Zn II, Mg I, and Cr II) to the Ni II lines assuming turbulent broadening (see, e.g., Prochaska & Wolfe 1997), leaving only the total column density as a variable. This yields a Zn II column density of \(\log(N(\text{Zn II})/\text{cm}^{-2}) = 12.96 \pm 0.03\), resulting in an updated metallicity of \([\text{M/H}] = -0.27 \pm 0.10\), consistent with the previous measurement. The VLT-UVES spectrum also showed absorption from the ground and excited fine structure states of neutral carbon (C I, C I\(^{+}\), and C II\(^{+}\)). A six-component fit of this complex is shown in Figure 1. The redshift, relative parameters of the C I lines are different from the other low-ionization lines, as this line traces the coldest components of the gas (e.g., Jorgenson et al. 2010). The total column densities of the different species are listed in Table 1.

2.2. ALMA Observations

The field surrounding QSO B1228–113 was observed with ALMA on UT 2017 April 7 and 8 with a compact configuration (maximum baseline of 453 m) for a total on-source integration time of 2.4 hr. One of the four spectral windows was centered on the redshifted CO(3–2) line at 108.3 GHz, and the remaining three spectral windows were set up to measure continuum emission. Callisto and Ganymede were used as flux calibrators, while QSO J1256–0547 and QSO J1216–1033 were used for bandpass and phase calibration, respectively.

The initial calibration was carried out using the ALMA pipeline in the Common Astronomy Software Applications (CASA; McMullin et al. 2007) package. The quasar continuum flux density (18.8 mJy; left panel of Figure 2) was sufficient to perform self-calibration, which was done in the Astronomical Image Processing System (AIPS; Greisen 2003) package. The continuum image was created in CASA using natural weighting, resulting in a synthesized beam of \(2.9'' \times 2.0''\) at −83°8 and a root mean square (rms) noise of 6.9 \(\mu Jy\) beam\(^{-1}\). The spectral cube was Hanning-smoothed to a velocity resolution of 43.2 km s\(^{-1}\). The resulting, naturally weighted spectral cube has a mean synthesized beam of \(2.6'' \times 1.8''\) at −83°4 and an rms of 0.15 mJy beam\(^{-1}\) per 43.2 km s\(^{-1}\) channel.

A clear emission line is detected in the continuum-subtracted spectral cube with a full width at half maximum (FWHM) of \(600 \pm 60\) km s\(^{-1}\) and a velocity-integrated flux density of \(0.73 \pm 0.06\) Jy km s\(^{-1}\) (Table 2 and Figure 3). The emission is spatially offset from the DLA by 3″5 at a position angle of −14°. Weak continuum emission is also detected at this location, with a flux density of \(46 \pm 10\) mJy (Figure 2). Both line and continuum emission from this source are spatially unresolved in the present ALMA images.

2.3. SINFONI Observations

The SINFONI spectrograph (Eisenhauer et al. 2003) on the VLT was used to obtain near-infrared integral field spectroscopy of the field surrounding QSO B1228–113 in program ID: 080.A-0742(A) (PI: Peroux; see Péroux et al. 2011). We re-reduced the

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\(^8\) https://github.com/linetools/linetools

Table 1

Properties of the Absorber

| DLA B1228–113 |
|----------------|
| R.A. (J2000)   | 12:30:55.62 |
| Decl. (J2000)  | −11:39:09.9 |
| Redshift       | 2.19289     |
| \(\log(N(\text{HI})/\text{cm}^{-2})\) | 20.60 ± 0.10 |
| \([\text{M/H}]\) | −0.27 ± 0.10 |
| \(\Delta v_{90}\) (km s\(^{-1}\)) | 163 ± 10 |
| \(\log(N(\text{Zn II})/\text{cm}^{-2})\) | 12.96 ± 0.03 |
| \(\log(N(\text{Mg I})/\text{cm}^{-2})\) | 13.34 ± 0.05 |
| \(\log(N(\text{Cr II})/\text{cm}^{-2})\) | 13.23 ± 0.06 |
| \(\log(N(\text{Ni II})/\text{cm}^{-2})\) | 14.05 ± 0.02 |
| \(\log(N(\text{C I})/\text{cm}^{-2})\) | 13.88 ± 0.08 |
| \(\log(N(\text{C I})^+/\text{cm}^{-2})\) | 14.0 ± 0.2 |
| \(\log(N(\text{C I})^+/\text{cm}^{-2})\) | <13.5 (2\(\sigma\)) |
| H I 21 cm Optical depth | <0.13 (3\(\sigma\)) |
| Covering factor, \(f\) | 0.93 |
| Spin temperature (K) | <1895 \times (f/0.93) |
data using the ESO SINFONI pipeline v. 2.9. The final co-added data cube was scaled to match the previously measured flux of the integrated QSO spectrum (Ellison et al. 2005). This was necessary because the response functions of the flux calibrators for each night showed variations of \( \pm 50\% \).

To measure possible \( \text{H} \alpha \) emission at the position of the ALMA CO(3–2) emission, we created a pseudo-narrowband image centered on the redshifted \( \text{H} \alpha \) line at 2095.5 \( \mu \text{m} \) from the SINFONI data cube. Any potential continuum emission was subtracted from this image by interpolating the flux in adjacent wavelength intervals blueward and redward of the \( \text{H} \alpha \) line. The one-dimensional spectrum (Figure 3, middle panel) was extracted with an aperture similar in size to the FWHM seeing of the observation. The spectrum shows an emission line that we identify as \( \text{H} \alpha \) at \( z = 2.1912 \). Besides \( \text{H} \alpha \), [N \( \text{II} \)] 6586 \( \AA \) is marginally detected as well. We fit both emission lines with the Image Reduction and Analysis Facility package (Tody 1993) using NGAUSSFIT and derived a total emission line flux of \( f(\text{H} \alpha) = (2.0 \pm 0.2) \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( f([\text{N} \text{II}]) = (0.5 \pm 0.3) \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \), consistent with the previous flux limits (Péroux et al. 2011).

### 2.4. GMRT Observations

The 250–500 MHz receivers of the Giant Metrewave Radio Telescope (GMRT) were used to carry out a search for redshifted HI 21 cm absorption from the DLA toward QSO B1228–113 on 2017 May 8. The GMRT Software Backend was used as the correlator with a bandwidth of 2.08 MHz centered at 444.85 MHz. The total velocity coverage is \( \approx 1400 \text{ km s}^{-1} \) at a velocity resolution of 2.7 \( \text{ km s}^{-1} \). The total on-source time was \( \approx 5 \text{ hr} \), with 25 working antennas.

The GMRT data were analyzed in AIPS using standard procedures for low-frequency imaging and spectroscopy (e.g., Kanekar et al. 2014). The final spectral cube has an rms noise of 1.7 \( \mu \text{Jy} \) per 2.7 \( \text{ km s}^{-1} \) channel, while the measured quasar continuum flux density is 340.4 \( \pm 0.6 \mu \text{Jy} \). The quasar spectrum shows no evidence for HI 21 cm absorption, yielding a \( 3\sigma \) upper limit on the velocity-integrated HI 21 cm optical depth of 0.13 \( \text{ km s}^{-1} \), assuming a Gaussian line profile with an FWHM of 20 \( \text{ km s}^{-1} \). This implies a \( 3\sigma \) lower limit of \( (238 \times f) \) K to the DLA spin temperature, where \( f \) is the DLA covering factor. Kanekar et al. (2009) used the Very Long Baseline Array (VLBA) to measure the core flux density of the quasar; combining the VLBA 327 MHz core flux density with the new GMRT total flux density yields a DLA covering factor of \( f = 0.93 \). The \( 3\sigma \) lower limit to the DLA spin temperature is then \( T_k > 1895 \times (f/0.93) \) K.

### 3. Results

#### 3.1. Galaxy Properties

We identify the line detected in the ALMA observations as the redshifted CO(3–2) emission line at \( z = 2.1933 \), in excellent agreement with the DLA absorption redshift, \( z = 2.19289 \). The velocity-integrated CO(3–2) flux density of 0.73 \( \pm 0.06 \) \( \text{Jy km s}^{-1} \) implies a CO(3–2) line luminosity of \( L_{\text{CO(3–2)}} = (1.88 \pm 0.15) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2 \) or \( L_{\text{CO(3–2)}} = (2.5 \pm 0.2) \times 10^7 L_\odot \).

![Figure 2](image.png)

**Figure 2.** Left: 100.5 GHz continuum image of the field surrounding QSO B1228–113. To highlight the continuum emission of fainter sources, we have subtracted out the QSO emission (which was detected at a very high signal-to-noise ratio). Gray contours start at 300\( \sigma \) and increase by 300\( \sigma \), whereas black contours start at 3\( \sigma \) and increase by \( \sqrt{2} \sigma \). Right: integrated CO(3–2) emission from the channels showing line emission (Figure 3). Contours begin at 3\( \sigma \) and increase by 2\( \sigma \). Dotted contours indicate negative values. The synthesized beam is shown in the bottom left inset.

### Table 2

**Properties of the Galaxy**

| ALMA J123055.50–113906.4 | R.A. (J2000) | 
|---------------------------|-------------|
|                           | 12:30:55.50 |
| Decl. (J2000)             | –11:39:06.4 |
| Redshift of CO(3–2) emission | 2.1933 ± 0.0005 |
| Redshift of H\( \alpha \)/[N \( \text{II} \)] emission | 2.1912 ± 0.0007 |
| \( S_{\text{cont}} \) at \( \nu_{\text{obs}} \) = 100.5 GHz (\( \mu \text{Jy} \)) | 46 ± 10 |
| FWHM of CO(3–2) (km s\(^{-1}\)) | 600 ± 60 |
| \( \int S_{\text{CO(3–2)}} d\nu \) (\( \mu \text{Jy km s}^{-1} \)) | 0.73 ± 0.06 |
| \( L_{\text{CO(3–2)}} \) (\( L_\odot \)) | (2.5 ± 0.2) \times 10^7 |
| \( L_{\text{CO(3–2)}} \) (\( \text{K km s}^{-1} \text{ pc}^2 \)) | (1.88 ± 0.15) \times 10^{10} |
| \( f(\text{H}\alpha) \) (\( \text{erg cm}^{-2} \text{ s}^{-1} \)) | (2.0 ± 0.2) \times 10^{-17} |
| \( f([\text{N} \text{II}]) \) (\( \text{erg cm}^{-2} \text{ s}^{-1} \)) | (0.5 ± 0.3) \times 10^{-17} |
| \( L_{\text{IR}} \) (\( L_\odot \)) | (2.2 ± 0.5) \times 10^{12} |
| \( M_{\text{mol}} \) (\( M_\odot \)) | (1.4 ± 0.2) \times 10^{11} |
| SFR (\( M_\odot \text{ yr}^{-1} \)) | 3.9 ± 0.4 |
| SFR_{dust-corrected} (\( M_\odot \text{ yr}^{-1} \)) | 110^{+50}_{-30} |

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**Note:** The table provides properties of the galaxy, including redshifts, FWHM values, and other relevant parameters. The values are measured using various techniques, including observations with ALMA and SINFONI, and are presented with uncertainties to reflect the precision of the measurements.
To estimate the total infrared luminosity (\(L(\text{TIR})\); defined as the integrated luminosity over the 8–1000 \(\mu\)m wavelength range) from the ALMA 100.5 GHz continuum image, we fitted a modified blackbody spectrum with mid-infrared slope, \(\alpha = 1.5\); spectral emissivity index, \(\beta = 1.5\); and dust temperature, \(T_{\text{dust}} = 35\) K, to the measured flux density (see, e.g., Neeleman et al. 2017). This yields a total infrared luminosity of \(L(\text{TIR}) = (2.2 \pm 0.5) \times 10^{12} L_\odot\). This estimate has a large systematic uncertainty (~0.6 dex) because both \(\beta\) and \(T_{\text{dust}}\) are not constrained by the single dust continuum measurement. We note, however, that this estimate is consistent with the estimate obtained from our \(L'(\text{CO})\) measurement, using the relationship between \(L'(\text{CO})\) and \(L(\text{TIR})\) in high-z galaxies (\(L(\text{TIR}) = (2.2 \pm 1.5) \times 10^{12} L_\odot\); see, e.g., Carilli & Walter 2013; Dessauges-Zavadsky et al. 2015).

From the \(H\alpha\) detection, we estimate a dust-uncorrected star formation rate (SFR) of \(3.9 \pm 0.4 M_\odot\) yr\(^{-1}\) (assuming a Kroupa initial mass function; Kennicutt & Evans 2012). Correcting this for dust obscuration using the total infrared luminosity (Kennicutt & Evans 2012) yields a dust-corrected SFR of \(110^{+30}_{-60} M_\odot\) yr\(^{-1}\), where the uncertainties include the systematic uncertainty on the total infrared luminosity. Comparison of the two SFRs suggest that the galaxy is highly dust-obsured, far more than typical galaxies at these redshifts (e.g., Moustakas et al. 2006). Only models with uncommonly low dust temperatures, \(T_{\text{dust}} \lesssim 25\) K, yield more typical dust-obscuration values, with dust-corrected SFRs \(\lesssim 20 M_\odot\) yr\(^{-1}\).

The molecular mass of the galaxy is estimated from the \(\text{CO}(3–2)\) line luminosity assuming a \(\text{CO}(3–2)\) to \(\text{CO}(1–0)\) line ratio of \(r_{31} = L'_{\text{CO}(3–2)}/L'_{\text{CO}(1–0)} = 0.57\) (Dessauges-Zavadsky et al. 2015) and a \(\text{CO}\) to \(\text{H}_2\) conversion factor of \(\alpha_{\text{CO}} = 4.3 M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\). These assumptions are valid for typical star-forming galaxies (Bolatto 2013), and yield a total molecular gas mass estimate of \(M_{\text{mol}} = (1.4 \pm 0.2) \times 10^{11} \times (\alpha_{\text{CO}}/4.3) \times (0.57/r_{31}) M_\odot\). This is at the upper end of the molecular gas mass distribution for star-forming galaxies at this redshift (Tacconi et al. 2013; Genzel et al. 2015). Note that if physical conditions are more akin to those in starburst galaxies, then \(\alpha_{\text{CO}} \approx 1 M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\) and \(r_{31} \approx 1\), yielding a molecular gas mass lower by a factor of \(\approx 10\). However, we disfavor this scenario, as even the dust-corrected SFR estimate is significantly below the median SFRs seen in starburst galaxies (e.g., Daddi et al. 2005). We emphasize that, despite the uncertainty in \(\alpha_{\text{CO}}\) and \(r_{31}\), this galaxy is likely massive, an assertion that is corroborated by the large \(\text{CO}(3–2)\) line width, FWHM \(\approx 600 \pm 60\) km s\(^{-1}\) (Tiley et al. 2016).

### 3.2. Galaxy/DLA Association

The agreement in redshift between the galaxy and DLA, as well as the low angular separation of the galaxy from the quasar sightline (\(\approx 3\)\(^\circ\)5 or \(\approx 30\) kpc at the DLA redshift), confirms the association between the molecular gas-rich galaxy and the high-metallicity absorber. This is consistent with results found at lower redshift, where CO emission studies of high-metallicity DLAs at \(z \approx 0.7\) (Møller et al. 2018; Kanekar et al. 2018) suggest that the cross-section for such DLAs appears to be biased toward galaxies with high molecular masses. Specifically, for five out of seven targeted intermediate-redshift, high-metallicity absorbers, a galaxy with high molecular gas mass was found within \(\approx 50\) kpc of the DLA and at the absorber redshift (Kanekar et al. 2018). Clearly, a larger sample of CO observations surrounding high-metallicity \(z \approx 2\) DLAs is needed to confirm this assertion at these redshifts.

Of course, there always is a possibility that the \(\text{Ly}\alpha\) absorption originates from a lower-mass galaxy below the sensitivity threshold of the present ALMA observations. However, the VLT-SINFONI observations yield an upper limit to the SFR of such a putative galaxy of \(< 0.9 M_\odot\) yr\(^{-1}\) (Péroux et al. 2011). In addition, we note that the excellent agreement in
velocity between the centroid of the CO emission and the low-ionization metal line absorption ($\approx 40 \text{ km s}^{-1}$; see Figure 3) disfavors scenarios where the absorber is probing gas with a bulk motion with respect to the galaxy—e.g., a single satellite galaxy or an extended disk—as in this case one would expect to see a net velocity offset between absorption and emission (Neeliman et al. 2016). The large velocity width of the DLA, $\Delta V_{90} = 163 \pm 10 \text{ km s}^{-1}$ (see, e.g., Prochaska & Wolfe 1997), is further evidence the DLA is associated with a more massive galaxy halo (e.g., Ledoux et al. 2006) and large stellar mass ($\log(M_*/M_\odot) \gtrsim 10.5$; Christensen et al. 2014).

3.3. Physical Conditions of the Absorbing Gas

The detection of C\textsc{i} in the UVES spectrum indicates the presence of cold dense gas in the DLA, as C\textsc{i} has been linked to the presence of molecular hydrogen (e.g., Srianand et al. 2005). The C\textsc{i} absorption in the $z = 2.19289$ DLA spans a wide range of velocities, indicating that the line-of-sight probes several distinct cold gas clumps. Interestingly, the strongest absorption component of the dominant low-ionization lines (e.g., Zn\textsc{ii}) at $v = 3 \text{ km s}^{-1}$ shows no C\textsc{i} absorption. This suggests that this component must be significantly warmer and less dense than the C\textsc{i}-bearing components.

This scenario is corroborated by our H\textsc{i} 21 cm absorption measurement. The high spin temperature ($T_s > 1895 \times (f/0.93) \text{ K}$) is inconsistent with the known anti-correlation between $T_s$ and metallicity [M/H] (Kanekar et al. 2014). If, however, we assume that the H\textsc{i} is predominantly associated with the strongest Zn\textsc{ii} absorption component, the metallicity of this gas is reduced to $\approx 0.7$, which is consistent with the $T_s$-[M/H] anti-correlation. We note that this requires that approximately 50% of the metals are locked up in the denser phase traced by C\textsc{i} and that this phase contributes little to the total H\textsc{i} column density.

This implies that either this phase is very metal-rich and small, thereby containing intrinsically little H\textsc{i} gas, or that most of the H\textsc{i} has been converted into H$_2$. However, a rough estimate of the H$_2$ column density from the expected scaling relations between C\textsc{i} and H$_2$ (Glover & Clark 2016) gives an H$_2$ column density of $4 \times 10^{18} \text{ cm}^{-2}$, well below the total H\textsc{i} content of the DLA but consistent with previous molecular hydrogen column density measurements in DLAs (e.g., Srianand et al. 2005). We therefore favor the first scenario whereby most of the metals are locked up in small metal-rich clumps. Similar multi-phase structure has been previously observed in a few high-z absorbers (e.g., Noterdaeme et al. 2017; Rudie et al. 2017). Alternatively, the high inferred spin temperature might arise if the sightline toward the radio core has a significantly lower H\textsc{i} column density than that toward the optical QSO (e.g., Wolfe et al. 2003; Kanekar et al. 2014).

4. Summary

We present, for the first time, molecular emission from a galaxy associated with a DLA at $z \approx 2.2$. Our results highlight the ability of ALMA to detect and characterize the galaxies associated with high-metallicity DLAs at the peak epoch of galaxy assembly. We obtain a high molecular gas mass, $M_{\text{mol}} = (1.4 \pm 0.2) \times 10^{11} \text{ (} \odot/4.3 \text{)} (0.57/r_{21}) M_\odot$, at the upper end of the mass distribution for star-forming galaxies at these redshifts (e.g., Tacconi et al. 2013; Genzel et al. 2015). The detection of far-infrared continuum with ALMA and weak H\alpha emission indicates significant amounts of dust obscuration and a dust-corrected SFR of $\approx 110^{+150}_{-50} M_\odot \text{ yr}^{-1}$.

The high molecular gas mass and large impact parameter ($\approx 30 \text{ kpc}$) are consistent with a scenario in which high-metallicity DLAs typically arise in the near vicinity of massive gas-rich galaxies. Finally, the detection and non-detection, respectively, of C\textsc{i} and H\textsc{i} 21 cm absorption suggest that the H\textsc{i} along the sightline is predominantly warm, but that there are several cold dense gas components that contain $\approx 50\%$ of the metals. The $z = 2.19289$ DLA toward QSO B1228+113 thus highlights the power of combining absorption spectroscopy with emission line studies in order to study the multi-phase structure of the gas surrounding high-redshift galaxies.

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