Metal Enrichment Leads to Low Atmospheric C/O Ratios in Transiting Giant Exoplanets

Néstor Espinoza1,2, Jonathan J. Fortney3, Yamila Miguel4, Daniel Thorngren5, and Ruth Murray-Clay3

1 Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
2 Millennium Institute of Astrophysics, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
3 Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA, USA
4 Laboratoire Lagrange, UMR 7293, Université de Nice-Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, Blvd de l'Observatoire, CS 34229, F-06304 Nice cedex 4, France
5 Department of Physics, University of California, Santa Cruz, CA, USA

Received 2016 November 28; revised 2017 February 11; accepted 2017 March 3; published 2017 March 24

Abstract

We predict the carbon-to-oxygen (C/O) ratios in the hydrogen–helium envelope and atmospheres of a sample of nearly 50 relatively cool (\(T_{\text{eq}} < 1000\) K) transiting gas giant planets. The method involves planetary envelope metallicity estimates that use the structure models of Thorngren et al. and the disk and planetary accretion model of Öberg et al. We find that nearly all of these planets are strongly metal-enriched, which, coupled with the fact that solid material is the main deliverer of metals in the protoplanetary disk, implies that the substellar C/O ratios of their accreted solid material dominate compared to the enhanced C/O ratio of their accreted gaseous component. We predict that these planets will have atmospheres that are typically reduced in their C/O compared to parent star values independent of the assessed formation locations, with C/O < 1 a nearly universal outcome within the framework of the model. We expect water vapor absorption features to be ubiquitous in the atmospheres of these planets, and by extension, other gas giants.

Key words: planet–disk interactions – planets and satellites: atmospheres – planets and satellites: composition – planets and satellites: formation – protoplanetary disks

1. Introduction

Over the past several years, there has been a significant push in exoplanet characterization to better understand the carbon-to-oxygen (C/O) ratios in the atmospheres of gas giant exoplanets. This has been in particular motivated by the connections that can potentially be made to the formation location and accretion history of the planets (see, e.g., Madhusudhan et al. 2011; Öberg et al. 2011; Madhusudhan 2012; Mordasini et al. 2016). This work is also quite timely given that the Juno Mission at Jupiter aims to measure the planet’s atmospheric water abundance via microwave emission and constrain the planet’s C/O, which impacts our knowledge of the planet’s interior structure and formation (Helley & Lunine 2014).

As is known in our solar system (Atreya et al. 2016), giant planet’s atmospheres need not take on the composition of their parent stars. Instead, the composition of the atmospheres is defined by the accretion of gas and solids, with the composition of these species dictated by the position of the planet in the protoplanetary disk, which in turn defines how much of each element is available in solid and gas form. This idea has been one of the key arguments in order to link planet formation and the composition of giant planet atmospheres (see, e.g., Madhusudhan et al. 2011; Öberg et al. 2011; Madhusudhan 2012).

There may well be additional tracers of formation and accretion history, but C/O ratios have driven the attention of the community mainly because of their potentially large observational effects. For example, water features in the infrared weaken or disappear in hot exoplanets for C/O \(> 1\) according to chemical equilibrium calculations because the water vapor abundance is strongly reduced (Madhusudhan 2012). This prediction has motivated several studies that aim to detect water vapor, in particular in transmission spectra, because the presence of a water feature could then constrain a low C/O ratio in those hot exoplanet atmospheres, even though the exact ratio cannot be determined.

Due to the presence of clouds, however, the detection of water vapor, and any first constraint on C/O ratios has been a very challenging problem (Sing et al. 2016). In fact, to date, the only transiting exoplanet for which the C/O ratio has been constrained with this technique is WASP-12b, which has been shown to have C/O < 1 at the terminator region (at 3\(\sigma\) confidence; Kreidberg et al. 2015). Other techniques have provided constraints as well. For example, the C/O ratios of the four directly imaged planets orbiting HR8799 have been recently estimated by Lavie et al. (2016), who suggest the two inner planets (at \(\sim 14\) and \(\sim 25\) au) show at least 30 times lower-than-stellar C/O ratios, while the two outer planets (at \(\sim 38\) and \(\sim 68\) au) show \(\sim 1.5\) larger-than-stellar C/O ratios.

Öberg et al. (2011) provided a partial framework for understanding the C/O ratio of gas giants within a simple disk, where the C/O ratio of the solids and gas were altered via condensation, which varies with the location of ice-lines. Typically, the condensation of H\(_2\)O and CO\(_2\) increase the C/O ratio of the remaining gas compared to solar abundances, while depressing the C/O of solids. This has been taken by much of the community as a “prediction” that planets that form in disks via core accretion, since they accrete potentially hundreds of Earth masses of gas, should be enhanced in C/O compared to their stars. However, this logic ignores the important, and potentially dominant, reservoir of C and O of the solid material in the disk.

Knowledge of the total amount of solid material accreted by gas giant planets could lead to a better understanding of the C/O ratio of their envelopes and visible atmospheres. For example, if the amount of solids accreted is negligible, then the composition of the planetary envelope will follow the composition of the gas in the protoplanetary disk, which can, if accreted in certain parts of the disk, allow for larger-than-stellar C/O ratios (Öberg et al. 2011; Öberg & Bergin 2016).
Similarly, if we knew that a planetary envelope and atmosphere is polluted with a large amount of solid material, then the atmosphere would have a lower-than-stellar C/O ratio, due to the oxygen-rich nature of the solid material in comparison with the gas in the disk.

There is a sample of planets for which we can make an assessment of the amount of accreted solids in their H/He-dominated envelopes. Thorngren et al. (2016) have recently shown, using a sample of 47 warm transiting giant exoplanets \((T_{\text{eq}} < 1000\,\text{K})\), whose radii are not affected by radius inflation processes, that these giant planets, as a class, are metal-enriched in comparison to their parent stars. In particular, their calculations show that these planets have metal masses that range from tens to hundreds of Earth masses, which therefore make up an important part of the bulk mass of the planets. Given that it is unlikely that all that mass is in the core, this suggests that the envelopes of these planets are highly enriched with metals, which is supported by models of planet accretion (Fortney et al. 2013; Venturini et al. 2015, 2016; Mordasini et al. 2016). Given that solid material is the main deliverer of metals in planetary envelopes, the work of Thorngren et al. (2016) provides us then with estimates for the amount of solid material in the envelopes of these exoplanets, which in turn can be used to estimate the C/O ratios in their envelopes.

In this Letter, we provide estimates for the C/O ratios for the sample of planets in Thorngren et al. (2016). We do this by using the simple static accretion model of Öberg et al. (2011), which assumes the envelope gas and solid material are accreted from the same region in the disk, although our main conclusions do not rest on the choice of accretion model. We detail the model and our calculations in Section 2 and discuss the implications for present and future observational studies of giant exoplanet atmospheres in Section 3.

2. Estimation of C/O Ratios

To estimate the C/O ratios of the Thorngren et al. (2016) planetary sample, we use the straightforward static planetary accretion model described by Öberg et al. (2011). Their framework gives the deviation of element \(X\) from the stellar value in an accreted planetary atmosphere as

\[
a_X = \frac{f_{X,s} M_s}{f_{sg} M_g} + (1 - f_{X,s}).
\]

where \(f_{X,s}\) is the fraction of element \(X\) bound in solids, \(f_{sg}\) is the grain-to-gas ratio in the disk (which, as in Öberg et al. 2011, we take to be equal to 0.01, the observed grain-to-gas ratio in the interstellar medium), \(M_s\) is the amount of mass in the envelope accreted in solids, and \(M_g\) is the amount of mass in the envelope accreted in gas. With this, the deviation of the C/O ratio of the planet compared to the star is given by \(a_C/a_O\).

In order to compute \(a_C\) and \(a_O\), we follow Öberg et al. (2011) and use the data in their Table 1, which compiles abundances and evaporation temperatures for CO, CO\(_2\), \(\text{H}_2\text{O}\), carbon grains, and silicates for conditions typical in a protoplanetary disk, which in turn allows us to compute the fraction of C and O bound in solids (i.e., \(f_{X,s}\) for \(X = \text{C}\) and \(X = \text{O}\)) for a given temperature, which we summarize in Table 1. In order to obtain the temperature at different positions in the protoplanetary disk, Öberg et al. (2011) use a simple disk temperature profile, which is a simple power-law profile of the form

\[
T(r) = T_0 \left(\frac{r}{1\,\text{au}}\right)^{-q}.
\]

where they set \(T_0 = 200\,\text{K}\) and \(q = 0.62\), which are average values for a large sample of protoplanetary disks (Andrews & Williams 2007). We use the same parametric profile here.

The key ingredient needed to estimate \(a_C/a_O\) for the sample of planets is bulk gas mass, \(M_g\), and mass accreted in solids, \(M_s\). In order to obtain these values we use the joint posterior distribution function (PDF) of the total estimated mass for each planet, \(M_{\text{tot}}\), and the estimated mass in metals, \(M_Z\). We obtain the latter with the method described in Thorngren et al. (2016). In short, the method uses the observed planetary masses, planetary radii, and system ages, along with giant planet thermal evolution/contraction models, to find solutions for the total metal mass with a planet that matches the measured radius at the given system age. These models place up to the first 10\(M_\oplus\) of metals in the core, while the rest of the metals that have to be added in order to match the observed radii are mixed in the (hydrogen-dominated) envelopes. In order to explore how the assumption of a 10\(M_\oplus\) core impacts our estimations, we repeat these calculations by assuming cores composed of 5\(M_\oplus\) and 15\(M_\oplus\), which clearly would yield either more or less metals in the envelope.

In order to estimate \(M_s\), we note that \(M_s\) can be written as a contribution between the core mass, \(M_c\) (whose hydrogen fraction we consider negligible), and the metals donated by the gas and the solids, i.e.,

\[
M_s = M_c + Z_g M_g + Z_s M_s.
\]

where \(Z_g\) and \(Z_s\) are the gas and solid metal fractions, respectively. \(M_{\text{tot}}\), on the other hand, can be written as the contribution between \(M_c\), \(M_g\), and \(M_s\), i.e.,

\[
M_{\text{tot}} = M_c + M_g + M_s.
\]

Finally, solving for \(M_s\) using Equations (1) and (2), we obtain

\[
M_s = \frac{M_c - Z_g M_{\text{tot}} - Z_s M_c}{Z_s - Z_g}.\]

In our calculations, we set \(Z_g = 0.01\) and \(Z_s = 1\) in this expression, which are typical values for protoplanetary disks where the gas is H/He-dominated. Note that \(M_s\) is easily obtained from these equations.

Ten thousand draws from the joint PDF (\(M_{\text{tot}}, M_Z\)) were obtained for each planet in order to obtain the joint PDF of \((M_c, M_s)\), which was used to estimate the PDF of \((a_C/a_O)\). Figures 1 and 2 show the results of this sampling scheme for accretion at different positions in the protoplanetary disk for planets with different core masses, which are color coded: 5\(M_\oplus\) (blue), 10\(M_\oplus\) (black), and 15\(M_\oplus\) (red). The planets are ordered

### Table 1

| Element | \(T > 135\,\text{K}\) | \(T > 47\,\text{K}\) | \(T > 20\,\text{K}\) |
|---------|-----------------|-----------------|-----------------|
| C       | 0.25            | 0.25            | 0.375           |
| O       | 0.32            | 0.52            | 0.66            |

Note. Fractions obtained using the data in Table 1 of Öberg et al. (2011).
In general, the predicted C/O ratio deviations for almost all planets fall under the stellar value (=1). The reasons for strongly substellar values are simple. First, the amounts of metals (our proxy for the accreted solids in the planetary envelopes) estimated in Thorngren et al. (2016) are quite large, typically tens of Earth masses, or even hundreds of Earth masses for super-Jupiters, far in excess of “solar composition.” Thus, the C/O ratio in the solid material in the disk, which has a large mass fraction of C and O, overweighs the C/O ratios of the accreted gas, which has little C or O, in setting the total C/O of the accreted envelope. This, in turn, suggests that the accretion of solids, rather than gas, is what defines the ratios in the envelopes of most giant exoplanets, in agreement with recent planet formation modeling work (Mordasini et al. 2016).

As can be observed in Figures 1 and 2, the assumed core mass has in general a very small but consistent effect: a larger core mass implies a higher (more stellar or superstellar) C/O ratio deviation. The effect is most noticeable for less massive planets, especially for the relatively low mass Kepler-30d and Kepler-89d because the estimated metal masses (5–15$M_\oplus$) are not significantly larger than the core masses considered here. This implies that if we assume core masses of the same order or higher for the estimated metal masses, then the planets are consistent with having all the metals sequestered in their cores (which is the reason why the case in which we assume core masses of $15M_\oplus$ is not shown in these figures for Kepler-30d, while the cases in which we assume 10 and $15M_\oplus$ cores are not shown for Kepler-89d). If this indeed was the case, then larger-than-stellar C/O ratios should be expected on the envelopes of those planets.

It is interesting to note that the deviations from the stellar C/O ratios of almost all the planets peak at (or very close to) the deviation from stellar C/O ratio of the solid material, which is the deviation expected when $M_c/M_\star \gg f_{c,5}/f_{g,5}$; in this limit, $a_{c,5}/a_\star \approx f_{c,5}/f_{g,5}$. For the case of accretion at distances smaller than 2 au (i.e., inward to the H$_2$O ice-line), the C/O ratio of the
solid material is 0.78, for accretion between 2 \( \lesssim r \lesssim 10 \) au (i.e., between the \( \text{H}_2\text{O} \) and \( \text{CO}_2 \) ice-lines) is 0.48, and for accretion between 10 \( \lesssim r \lesssim 40 \) au (i.e., between the \( \text{CO}_2 \) and CO ice-lines) is 0.57; as can be seen in Figures 1 and 2, most distributions of the C/O ratio deviations for the planets in our sample peak closer to those values. In Figure 3, we plot the median deviation for all the planets studied in this work along with the 16th and 84th percentile of the sample peak closer to those values. In Figure 3, we plot the deviation of the gas and solid material for the different elements considered in the figure.

### 3. Discussion

In the present work, we have estimated C/O ratio deviations for the 47 warm giant exoplanets studied in Thorngren et al. (2016), and for which estimates of the amount of metals, here used as a proxy of the solid material in the envelopes, are available. Using a simple static model of planetary accretion, we estimate that most planets have lower-than-stellar C/O ratios in their envelopes, given their overall strongly metal-enriched nature.

If we couple this result with the observational determination that most stars have C/O ratios lower than 1 (Nissen et al. 2014; Teske et al. 2014; Brewer & Fischer 2016), then this implies that we estimate C/O < 1 for most of the planets in the sample of Thorngren et al. (2016), independent of where the planet formed as long as (1) it was formed inward to the CO ice-line (which is the expected formation location in the core accretion scenario; see, e.g., Lissauer 1993; Armitage 2007 and references therein), (2) the envelope is well mixed with minimal metallicity gradient (expected for the masses of the planets being considered in this work; see Mordasini et al. 2016), and (3) the accreted solids are oxygen-rich in relation to the gas (which is expected in typical conditions in disks; see, e.g., Pontoppidan 2006; Oberg et al. 2011).

The atmospheric characterization of warm exoplanets like the ones studied in this work via spectroscopy would be ideal in order to test our findings. However, due to their cool atmospheres and corresponding small scale-heights, and their potentially cloudy nature, the constraints that can be put on their C/O ratios today is quite challenging (see, e.g., the case of HAT-P-11b; Fraine et al. 2014). If hotter giant exoplanets follow similar formation paths as their warm counterparts, however, this means that most of them will also have C/O ratios of less than one, which would in turn imply that water features should be ubiquitous in their atmospheres if equilibrium conditions hold (Madhusudhan 2012; Kreidberg et al. 2015), as long as their atmospheres are clear of clouds and are representative of the bulk C/O ratios in their envelopes. Low C/O ratios have indeed been constrained in HD 209458b (Brogi et al. 2016) and WASP-12b (under equilibrium conditions; Kreidberg et al. 2015; but see Hansen et al. 2014; Stevenson et al. 2014); however, for other exoplanets it is unclear what constraints the observed water signatures impose on their water abundances (Sing et al. 2016; Barstow et al. 2017). Brown dwarfs spectra could also provide a useful comparison sample to our giant planet population; however, it is unclear if they form in disks around stars. The very wide diversity in C/O ratios obtained for T dwarfs (Line et al. 2016; Madhusudhan et al. 2016a) could be due to chemical sequestration of O in condensates, a variety of formation mechanisms for the objects, or imperfections in opacity databases.
It is interesting to note that our model works nicely for our own solar system giant planets, Jupiter and Saturn. In Figure 4, we show estimations for \(a\text{C}/(C/H)\) using our model for these planets, assuming different core masses to obtain \(M_Z\) as in Section 2, and compare them to the values estimated in Atreya et al. (2016) using data from the Galileo and Cassini missions. As can be seen, there is good agreement within the error bars and the uncertainty given by the core mass in our models. We can also use our model to estimate Jupiter’s O/H, which is timely, as NASA’s Juno mission is going to measure this value soon (Janssen et al. 2005; Helled & Lunine 2014). Our model suggests \(a\text{O} \pm 1\) values of 2.9–3.9, 4.1–5.7, and 5.0–7.0 for formation inside the H\(_2\)O, between the H\(_2\)O and CO\(_2\), and between the CO\(_2\) and CO ice-lines, respectively, slightly larger than the ones predicted in, e.g., Mouissi et al. (2012) and Wang et al. (2015). These values should be taken with care, however, as (1) Jupiter’s internal structure (and, thus, \(M_Z\)) depends on the equations of state and the accuracy of the observational constraints (e.g., gravitational moments; see, e.g., Saumon & Guillot 2004; Miguel et al. 2016 and references therein) and (2) the distribution of \(M_Z\) in Jupiter might be inhomogeneous.

Several additional steps could be taken if one wanted to perform a more detailed estimation of the C/O ratios of the studied planets. First, the abundances of carbon and oxygen bearing elements, which were obtained from the work of Pontoppidan (2006), might change from disk to disk. Second, radial drift of the material in the disk and gas accretion should be taken into account in order to estimate how the snowlines and the abundances of the different elements that define the changes in the C/O ratios in the disk at the distances proved here (i.e., H\(_2\)O, CO\(_2\), CO) evolve in the disk (Piso et al. 2015). Third, the (planetary and disk) time evolution with respect to variables such as pressure and temperature should be considered (Mordasini et al. 2016). The effect of implementing all these more detailed processes would be, in general, to shift the ice-lines inward in the protoplanetary disk. Furthermore, although the relative amount of oxygen and carbon in solids and gas might change, the fact that solids are oxygen-rich seems to be a reasonable assumption (Mordasini et al. 2016; Wilson et al. 2016). The detailed impact of these effects is outside the scope of this work, whose aim was to show an alternative interpretation to the typical picture of envelope accretion in protoplanetary disks, in which gas accretion is suggested to be the main character that defines important abundance tracers such as the C/O ratio in planetary envelopes (e.g., Öberg et al. 2011; Cridland et al. 2016; Madhusudhan et al. 2016b; Öberg & Bergin 2016). Given that giant planets are heavily metal-enriched compared to their parent stars, we suggest that it is in fact the solids, and not the gas, that are the key ingredient that defines these tracers in the envelopes of giant exoplanets.

We would like to thank the anonymous referee for useful suggestions that improved this article. N.E. and Y.M. wish to acknowledge support from the Kavli Summer Program in Astrophysics. N.E. acknowledges support of the VRI/PUC grant, the CONICYT-PCHA/Doctorado Nacional graduate fellowship and support from the Ministry for the Economy, Development and Tourism Programa Iniciativa Científica Milenio through grant IC 12009, awarded to the Millennium Institute of Astrophysics (MAS). J.J.F. acknowledges the support of NSF grant NNX16AB49G. Y.M. greatly appreciates the CSP post-doctoral fellowship program. N.E. would like to thank R. Brahm and A. Jordan for useful discussions.

References

Andrews, S. M., & Williams, J. P. 2007, ApJ, 659, 705
Armitage, P. J. 2007, arXiv:astro-ph/0701485
Atreya, S. K., Crida, A., Guillot, T., et al. 2016, arXiv:1606.04510
Barstow, J. K., Aigrain, S., Irwin, P. G. J., & Singh, D. K. 2017, ApJ, 834, 50
Brewer, J. M., & Fischer, D. A. 2016, ApJ, in press (arXiv:1608.06286)
Brogi, M., Line, M., Bean, J., Désert, J.-M., & Schwarz, H. 2016, ApJL, submitted (arXiv:1612.07008)
Cridland, A. J., Pudritz, R. E., & Alesi, M. 2016, MNRAS, 461, 3274
Fortney, J. J., Mordasini, C., Nettelmann, N., et al. 2013, ApJ, 775, 80
Fraine, J., Deming, D., Benneke, B., et al. 2014, Natur, 513, 526
Hansen, C. J., Schwartz, J. C., & Cowan, N. B. 2014, MNRAS, 444, 3632
Helled, R., & Lunine, J. 2014, MNRAS, 441, 2273
Janssen, M. A., Hofstadter, M. D., Gulkis, S., et al. 2005, Icar, 173, 447
Keidberg, L., Line, M. R., Bean, J. L., et al. 2015, ApJ, 814, 66
Lavie, B., Mendonça, J. M., Mordasini, C., et al. 2016, arXiv:1610.03216
Line, M. R., Marley, M. S., Liu, M. C., et al. 2016, ApJ, submitted (arXiv:1612.02809)
Lissauer, J. J. 1993, ARA&A, 31, 129
Madhusudhan, N. 2012, ApJ, 758, 36
Madhusudhan, N., Apai, D., & Gandhi, S. 2016a, ApJ, submitted (arXiv:1612.03174)
Madhusudhan, N., Bitsch, B., Johansen, A., & Eriksen, L. 2016b, MNRAS, submitted (arXiv:1611.03083)
Madhusudhan, N., Harrington, J., Stevenson, K. B., et al. 2013, Natur, 496, 64
Miguel, Y., Guillot, T., & Fayon, L. 2016, A&A, 596, A114
Mordasini, C., van Boekel, R., Mollière, P., Henning, T., & Benneke, B. 2016, ApJ, 832, 41
Mousis, O., Lunine, J. I., Madhusudhan, N., & Johnson, T. V. 2012, ApJL, 751, L7
Nissen, P. E., Chen, Y. Q., Carigi, L., Schuster, W. J., & Zhao, G. 2014, A&A, 568, A25
Öberg, K. I., & Bergin, E. A. 2016, ApJL, 831, L19
Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, ApJL, 743, L16
Piso, A.-M. A., Öberg, K. I., Bornstiel, T., & Murray-Clay, R. A. 2015, ApJ, 815, 109
Pontoppidan, K. M. 2006, A&A, 453, L47
Saumon, D., & Guillot, T. 2004, ApJ, 609, 1170
Sing, D. K., Fortney, J. J., Nikolov, N., et al. 2015, Natur, 529, 59
Stevenson, K. B., Bean, J. L., Madhusudhan, N., & Harrington, J. 2014, ApJL, 791, 36
Teske, J. K., Cunha, K., Smith, V. V., Schuler, S. C., & Griffith, C. A. 2014, ApJ, 788, 39
Thorngren, D. P., Fortney, J. J., Murray-Clay, R. A., & Lopez, E. D. 2016, ApJ, 831, 64
Venturini, J., Alibert, Y., & Benz, W. 2016, A&A, 596, A90
Venturini, J., Alibert, Y., Benz, W., & Ikoma, M. 2015, A&A, 576, A114
Wang, D., Gierasch, P. J., Lunine, J. I., & Mousis, O. 2015, Icar, 250, 154
Wilson, D. J., Gänscicke, B. T., Farhi, J., & Koester, D. 2016, MNRAS, 459, 3282