Carbon X-ray absorption in the local ISM: fingerprints in X-ray Novae spectra

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ABSTRACT
We present a study of the C K-edge using high-resolution LETGS Chandra spectra of four novae during their super-soft-source (SSS) phase. We identified absorption lines due to C ii Kα, C iii Kα and C iii Kβ resonances. We used these astronomical observations to perform a benchmarking of the atomic data, which involves wavelength shifts of the resonances and photoionization cross-sections. We used improved atomic data to estimate the C ii and C iii column densities. The absence of physical shifts for the absorption lines, the consistence of the column densities between multiple observations and the high temperature required for the SSS nova atmosphere modeling support our conclusion about an ISM origin of the respective absorption lines. Assuming a collisional ionization equilibrium plasma the maximum temperature derived from the ratio of C ii/C iii column densities of the absorbers correspond to $T_{\text{max}} < 3.05 \times 10^4 \text{K}$.

Key words: ISM: structure – ISM: atoms – X-rays: ISM

1 INTRODUCTION
High-resolution X-ray spectroscopy constitutes a powerful technique to study the elements associated with the local interstellar medium (ISM), defined as gas and dust between the stars. By using an X-ray bright source, acting as a lamp, the absorption features identified in the X-ray spectra provide information about the physical properties of the gas between the source and the observer. Using X-ray spectra of low mass X-ray binaries (LMXBs) the O, Fe, Ne, Mg and Si K absorption edges associated to the ISM have been analyzed in previous works (Juett et al. 2004; Ueda et al. 2005; Juett et al. 2006; Yao et al. 2009; Pinto et al. 2010, 2013; Costantini et al. 2012; Gatuzz et al. 2013a,b; Liao et al. 2013; Luo & Fang 2014; Gatuzz et al. 2014, 2015; Schulz et al. 2016; Gatuzz et al. 2016; Nicastro et al. 2016a,b; Joachimi et al. 2016; Gatuzz & Churazov 2018).

The ISM is composed of multiple phases which depends on their characteristic temperatures and densities. Carbon, which constitutes the fourth most abundant element in the Galaxy, can be used to probe the link between the different phases. C i, for example, has been used to analyze the cold Galactic gas which is characterized by a relatively low thermal pressure using the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (Jenkins & Tripp 2001; Burgh et al. 2010; Jenkins & Tripp 2011), while the C ii 158 µm line allows the characterization of the cold atomic clouds in transition from atomic to molecular form (Pineda et al. 2013; Langer et al. 2014; Pineda et al. 2014, 2017; Richter et al. 2017; Savage et al. 2017). Also, it has been shown that solids that contain carbon atoms, such as graphite and polycyclic aromatic hydrocarbons, may constitute the main heat source for the ISM (Draine & Li 2001; Helou et al. 2001; Okada et al. 2013; Chen et al. 2017; Shannon et al. 2018). In this sense, it is essential to estimate the amount of C depleted in the dust phase in order to fully understand the heating-cooling ISM processes.

One of the advantages of the high-resolution X-ray spectroscopy is that it provides access to both gas and solid components of the ISM. The C K-edge, located at 38-44 Å wavelength, can be accessed only through the low-energy transmission grating (LETG) on board of the Chandra ob-

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Figure 1. \( \text{C} \equiv \text{K}\alpha \) resonances observational wavelengths determined from Gaussian fits. The horizontal grey region correspond to the average value and its 90% uncertainty.

2 OBSERVATIONS AND DATA REDUCTION

We analyze \textit{Chandra} spectra of four SSS in order to study the ISM carbon K-edge along different lines of sight. Because of their brightness and proximity, SSS high-resolution spectra constitute a useful way to analyze not only the binary system involved but also the ISM fingerprints identified as absorption features. Table 1 lists the specifications for each LETGS-HRC observation, the observation date, the exposure time, the hydrogen column density 21 cm measurement from the Kalberla et al. (2005) survey, the count rate and the number of counts in the C K-\( \alpha \) wavelength region (38–44 Å). The data were reduced using the Chandra Interactive Analysis of Observations software (CIAO, version 4.9) and following the standard procedure to obtain the Low-Energy Transmission Grating (LETG) spectra. For each observation we combine the +1/-1 orders using the \texttt{combine_grating_spectra} script. We use the \texttt{xspec} analysis data package (Arnaud 1996, version 12.9.1) to perform the spectral fitting. Finally, we use \( \chi^2 \) statistic with the weighting method for low counts regime defined by Churazov et al. (1996).

3 C K-EDGE MODELING

In order to analyze the C K-edge absorption region (38–44 Å) we first used a functional model consisting of a power law continuum with absorption lines described by Gaussian profiles. Table 2 shows the wavelength position for all absorption lines identified in the spectra as well as their average values. Theoretical values, obtained from Hasoglu et al. (2010) calculations, are also listed. Both cameras, the High Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS) have C i instrumental absorption at \( \sim 43.6 \) Å due to absorption edges in the materials comprising the instruments, as is indicated by the Chandra Proposers’ Observatory Guide. We have not identified C i absorption lines in excess of instrumental features that could be associated with the ISM in the X-ray spectra sample. In this sense, it has been shown that the C i column density associated to the ISM tends to be lower than \( 10^{14} \) cm\(^{-2} \) along multiple line-of-sights, including regions with large HI column densities (Jenkins & Tripp 2011; Gerin et al. 2015; Welty et al. 2016; Pineda et al. 2017).

Figure 1 shows the wavelength positions for each resonance in the \( \text{C} \equiv \text{K}\alpha \) triplet, which have been measured in all observations. It is important to note that, considering the uncertainties, the wavelength positions tend to agree not only between different observations of the same source but also for different sources. \( \text{C} \equiv \text{K}\alpha \) and \( \text{C} \equiv \text{K}\beta \) absorption lines were identified in 7 and 5 observations, respectively. Figure 2 shows the best-fit wavelength positions measured for both resonances. In both figures the horizontal grey regions indicate the average values and their uncertainties. It is clear from the plots that, considering the uncertainties, the wavelength positions do not show significant shift between observations.

1 http://cxc.harvard.edu/ciao/threads/gspec.html
2 https://heasarc.gsfc.nasa.gov/xanadu/xspec/
3 http://cxc.harvard.edu/proposer/POG/html/index.html
Table 1. List of Chandra LETGS-HRC observations.

| Source   | ObsID. | Obs. date | Exp. time (ks) | N(HI) (10^{21} cm^{-2}) | count-rate (counts/s) | Counts (38–44 Å) |
|----------|--------|-----------|----------------|--------------------------|------------------------|------------------|
| KTEri    | 12097  | 23-01-2010| 14.9           | 0.52                     | 11.52                  | 25028            |
|          | 12100  | 31-01-2010| 27.9           | 77.73                    | 18377                  |                  |
|          | 12101  | 06-02-2010| 47.8           | 37.48                    | 16971                  |                  |
| Sgr2015b | 12203  | 21-04-2010| 32.4           | 106.5                    | 26717                  |                  |
|          | 16690  | 16-10-2015| 48             | 1.11                     | 12.07                  | 106572           |
| V339Del  | 15742  | 09-11-2013| 46             | 1.23                     | 68.31                  | 352919           |
|          | 15743  | 06-12-2013| 49             | 48.34                    | 293788                 |                  |
| V4743Sgr | 3775   | 19-03-2003| 20.3           | 1.05                     | 38.91                  | 45173            |
|          | 3776   | 18-07-2003| 11.7           | 37.16                    | 26349                  |                  |
|          | 4435   | 25-09-2003| 12.0           | 19.78                    | 16209                  |                  |

N(HI) column densities obtained from Kalberla et al. (2005).

Table 2. Absorption line assignments with observed wavelength.

| Source   | ObsID. | CII Kα1 (Å) | CII Kα2 (Å) | CII Kα3 (Å) | CII Kα (Å) | CII Kβ (Å) |
|----------|--------|--------------|--------------|--------------|-------------|-------------|
| Theoretical |   | 43.0592 | 42.9867 | 42.6818 | 42.2360 | 38.4459 |
| KTEri    | 12097 | 43.0599 ± 0.0043 | 42.9653 ± 0.0043 | 42.7838 ± 0.0043 | 42.2091 ± 0.0042 | 38.4100 ± 0.0038 |
| 12100 | 43.0736 ± 0.0039 | 43.0000 ± 0.0039 | 42.7863 ± 0.0039 | – | – |
| 12101 | 43.0623 ± 0.0047 | 42.9875 ± 0.0047 | 42.7626 ± 0.0047 | 42.2042 ± 0.0046 | – |
| 12203 | 43.0725 ± 0.0047 | 43.0002 ± 0.0047 | 42.7748 ± 0.0047 | – | – |
| Sgr2015b | 16690 | 43.0622 ± 0.0034 | 42.9756 ± 0.0034 | 42.7766 ± 0.0034 | – | – |
| V339Del  | 15742 | 43.0703 ± 0.0043 | 42.9875 ± 0.0043 | 42.7707 ± 0.0043 | 42.1873 ± 0.0042 | 38.4093 ± 0.0038 |
| 15743 | 43.0642 ± 0.0047 | 42.9906 ± 0.0047 | 42.7800 ± 0.0047 | 42.1752 ± 0.0046 | 38.4082 ± 0.0042 |
| V4743Sgr | 3775 | 43.0725 ± 0.0039 | 42.9847 ± 0.0039 | 42.7666 ± 0.0038 | 42.1878 ± 0.0038 | 38.4039 ± 0.0035 |
| 3776 | 43.0684 ± 0.0043 | 42.9795 ± 0.0043 | 42.7748 ± 0.0043 | 42.1615 ± 0.0042 | 38.4133 ± 0.0038 |
| 4435 | 43.0684 ± 0.0043 | 42.9847 ± 0.0043 | 42.7751 ± 0.0043 | 42.1840 ± 0.0043 | 38.4089 ± 0.0038 |

Average | | 43.0694 ± 0.0074 | 42.9851 ± 0.0074 | 42.7751 ± 0.0074 | 42.1840 ± 0.0043 | 38.4089 ± 0.0038 |

Figure 2. Left pannel: C III Kα resonance observational wavelengths determined from Gaussian fits. Right pannel: C III Kβ resonance observational wavelengths determined from Gaussian fits. The horizontal gray region corresponds to the average value and its 90% uncertainty.
Figure 3. C\textsc{i}, C\textsc{ii} and C\textsc{iii} photoabsorption cross sections computed by Hasoglu et al. (2010) that are implemented in the ISMabs model. Vertical dashed lines correspond to the average measurements listed in Table 1. Left panel displays the original cross sections while right panel shows the same curves after the benchmarking.

Figure 4. Best fit results using Chandra LETG data for the C\textsc{ii} K-edge wavelength region. Lines correspond to the model before and after the atomic data benchmarking (red dashed and blue solid lines, respectively)
It is clear that the resonance positions for the Kα transitions differ between the theoretical predictions and the observational measurements. In this sense we have adjusted the cross sections after the wavelength corrections. It is important to mention that such benchmarking has been performed previously for the oxygen and neon photoabsorption cross-sections by Gatuzz et al. (2013a,b, 2015) concluding that the Chandra wavelength calibration can be safely used to correct the theoretical wavelength resonance positions.

We performed a benchmarking of the atomic data by comparing the observed and theoretical absorption lines in the C K-edge region. Left panel in Figure 3 shows the C i (black line), C ii (red line) and C iii (blue line) photo-absorption cross sections computed by Hasoglu et al. (2010). Vertical lines correspond to the average measurements listed in Table 1. It is clear that the resonance positions for the Kα transitions differ between the theoretical predictions and the observational measurements. In this sense we have adjusted cross sections in order to obtain the best possible agreement with the observed lines. The shifts are +10.2 mÅ, −1.59 mÅ, and +93.3 mÅ for the C ii Kα1, Kα2 and Kα3 resonances, respectively. The larger shift for the Kα3 is expected because the n = 3 resonances carry the greatest energy uncertainty along a Rydberg series (Hasoglu et al. 2010). For C iii we move the Kα and the whole cross-section by −52 mÅ, and −37 mÅ, respectively. From the theoretical point of view, a ∼ 59 mÅ under-prediction in wavelength is expected (Hasoglu et al. 2010). Right panel in Figure 3 shows the cross sections after the wavelength corrections. It is important to mention that such benchmarking has been performed previously for the oxygen and neon photoabsorption cross-sections by Gatuzz et al. (2013a,b, 2015) concluding that the Chandra wavelength calibration can be safely used to correct the theoretical wavelength resonance positions.

Figure 5. Left panel: C ii column densities obtained from the best ISMabs fit. Right panel: C iii column densities obtained from the best ISMabs fit.

Table 3. Column density best-fit results.

| Source   | ObsID. | N(CII) | N(CIII) | CII/CIII |
|----------|--------|--------|---------|----------|
| KTEri    | 12097  | 18.63±2.99 | 0.58±0.58 | 32.12±27.00 |
|          | 12100  | 19.51±3.44 |          |          |
|          | 12101  | 20.81±3.79 |          |          |
|          | 12203  | 20.36±1.11 |          |          |
| Sgr2015b | 16690  | 33.50±2.44 |          |          |
|          | 16691  | 35.06±2.47 |          |          |
| V339Del  | 15742  | 24.98±1.89 | 0.53±0.14 | 47.13±12.11 |
|          | 15743  | 22.91±1.92 | 0.65±0.15 | 35.24±8.51 |
| V4743Sgr | 3775   | 32.28±3.36 |          |          |
|          | 3776   | 29.50±1.84 | 1.26±0.58 | 23.41±10.24 |
|          | 4435   | 31.19±4.40 | −0.98±0.95 | 35.04±31.37 |

Column densities in units of 10¹-six cm⁻².

We included the corrected cross-sections from Hasoglu et al. (2010) in the ISMabs⁴ model in order to estimate C ii and C iii column densities in the SSS spectra listed in Table 1. Figure 4 shows the best-fit results using the ISMabs model for the C ii K-α wavelength region (42.5–43.3 Å). In each panel, black data points correspond to the observation. The model before the atomic data corrections and after the correction are indicated (red dashed and blue solid lines, respectively). In all cases we obtained a data fitting improvement of Δχ² > 20. Table 3 lists the column densities obtained for each observation. Due to the elemental abundance enrichments in the ejected material from the respective novae explosion through the mixing process (Kelly et al. 2013), differences between column densities for observations performed at different epochs are expected if the absorbing material is intrinsic to the source. Figure 5 shows a comparison between the column densities obtained from the ISMabs model. It is clear from the plot that the column densities tend to agree for different observations of the same source. Differences between sources, on the other hand, are expected due to the density distribution of the ISM gas along the Galaxy (Robin et al. 2003; Kallman et al. 2009; Nicastro et al. 2016a,b; Gatuzz & Churazov 2018).

Another possibility is an origin in the SSS atmosphere which usually shows multiple absorption features (Orio 2012; Ness 2012; Ness et al. 2013). However, such atmospheres require high temperatures (> 0.6MK), for which we will not find C i, C ii and C iii ions (Ness et al. 2009; Rauch et al. 2010; van Rossum 2012; Rauch 2016). It is important to compare the 1–2 months observation separation time in our sample with the nova evolution time-scale, which can vary from months to years (Schwarz et al. 2011). For example, Ness et al. (2007) modeled the X-ray high-resolution spectra of the RS Ophiuchi nova, a source that shows a notable evolution in both, the continuum and the emission/absorption features, within months (see Figure 1 in Ness et al. 2009). The model used by Ness et al. (2007) included a compo-

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⁴ https://heasarc.gsfc.nasa.gov/xanadu/xspec/models/ismabs.html
Figure 6. C II $\lambda 1335$ (top panels) and C VI $\lambda 4959$ (bottom panels) absorption lines parametrized in velocity space for each source analyzed.

Figure 7. C II/C III ratio obtained from xstar calculations assuming collisional ionization equilibrium plasma. Horizontal dashed lines correspond to the ratios listed in Table 3. The arrow indicates the maximum temperature obtained.

normalized for the ISM local absorption and a second component to model the circumstellar material intrinsic to the source. The best-fit requires that the oxygen contribution from the circumstellar material disappears around day 54 after the outburst, probably due to photoionization of the local gas by the radiation field.

Figure 6 shows a comparison between C II $\lambda 1335$ (top panels) and C VI $\lambda 4959$ (bottom panels) absorption lines parametrized in velocity space for each source analyzed in this work. The C VI $\lambda 4959$ absorption line has been identified as intrinsic to the source previously (Ness et al. 2003; Petz et al. 2005; Ness et al. 2007; Ness 2012; van Rossum 2012). It is clear from the plot that the C II $\lambda 1335$ remains at the same wavelength while there are no C VI $\lambda 4959$ absorption features at rest wavelength. Also, some high-resolution X-ray novae spectra have shown P Cygni profiles (Ness et al. 2007; Orio et al. 2013) which we have not identified in the analyzed spectra.

It is important to note that there is no a reliable method to determine the total amount of carbon emitted in X-ray ejecta, in order to compare with the ISM abundance. Theoretical estimation, such as Rauch et al. (2010), depends on multiple factors including the composition of the accreted material, nuclear burning products, composition of the white dwarf and the amount of mixing of white dwarf material into the ejecta.

Table 3 also list the C II/C III ratios for those sources for which both column densities can be estimated. It is clear that C II dominates in all cases. In this sense, previous analysis using Herschel Galactic observations show that C II constitutes the main carbon reservoir along the lines of sight in most cases (Pineda et al. 2014; Gerin et al. 2015). The ion fractions depend on the physical state of the plasma. We used the xstar$^5$ code to estimate the maximum temperature of the gas assuming collisional ionization equilibrium (see Gatuzz & Churazov 2018). Figure 7 shows the C II/C III ra-

\footnote{https://heasarc.gsfc.nasa.gov/lheasoft/xstar/xstar.html}
ratio obtained from the xSTAR calculations. Horizontal dashed lines correspond to the ratios listed in Table 3 while the vertical arrow indicates the maximum temperature derived. We found $T_{\text{max}} < 3.05 \times 10^4$ K.

5 CONCLUSIONS AND SUMMARY

We have performed an analysis of the C K-edge using high-resolution Chandra spectra of four SSS. The instrumental features due to a C layer in the camera prevent the analysis of C i absorption. We have detected all three resonances of the C ii Kα in 11 observations as well as the C iii Kα and Kβ in 7 and 5 observations, respectively. We used the astronomical observations in order to perform a benchmarking of the atomic data computed by Hasoglu et al. (2010). We have included these corrected cross-sections in the ISMabs X-ray absorption model. Using the improved atomic data we estimated the C ii and C iii column densities for each observation. While high-ionized lines such as C vi Kα show significant shifts between different observations and different sources, the C ii and C iii wavelength positions are consistent. The absence of physical shifts for the absorption lines, the lack of variability for the column densities between different observations and the low temperatures associated to these ions compared to X-ray novae typical atmosphere temperature support our conclusion about an ISM origin of the absorption lines identified in the spectra. From the ratios of C ii/C iii column densities, we found $T_{\text{max}} < 3.05 \times 10^4$ K, which corresponds to the so-called warm component of the ISM.

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REFERENCES

Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17
Burgh E. B., France K., Jenkins E. B., 2010, ApJ, 708, 334
Chen X. H., Li A., Zhang K., 2017, ApJ, 850, 104
Churazov E., Gillanov M., Forman W., Jones C., 1996, ApJ, 471, 673
Costantini E., et al., 2012, A&A, 539, A32
Draine B. T., Li A., 2001, ApJ, 551, 807
Gautuzz E., et al., 2013a, ApJ, 768, 60
Gautuzz E., et al., 2013b, ApJ, 778, 83
Gautuzz E., García J., Mendoza C., Kallman T. R., Bautista M. A., Gorczyca T. W., 2014, ApJ, 790, 131
Gautuzz E., García J., Kallman T. R., Mendoza C., Gorczyca T. W., 2015, ApJ, 800, 29
Gautuzz E., García J., Kallman T. R., Mendoza C., 2016, A&A, 588, A111
Gautuzz E., Churazov E., 2018, MNRAS, 474, 696
Gerin M., et al., 2015, A&A, 573, A30
Helou G., Malhotra S., Hollenbach D. J., Dale D. A., Contursi A., 2001, ApJ, 548, L73
Hasoglu M. F., Abdel-Naby S. A., Gorczyca T. W., Drake J. J., McLaughlin B. M., 2010, ApJ, 724, 1296
Jenkins E. B., Tripp T. M., 2001, ApJS, 137, 297
Jenkins E. B., Tripp T. M., 2011, ApJ, 734, 65
Joachimi K., Gautuzz E., García J. A., Kallman T. R., 2016, MNRAS, 461, 352
Juett A. M., Schulz N. S., Chakraborty D., 2004, ApJ, 612, 308
Juett A. M., Schulz N. S., Chakraborty D., Gorczyca T. W., 2006, ApJ, 648, 1066
Kalberla P. M. W., Burton W. B., Hartmann D., Arnal E. M., Bajaja E., Morris R., Poppel W. G. L., 2005, A&A, 440, 775
Kallman T. R., Bautista M. A., Gorciel A., Mendoza C., Miller J. M., Palmeri P., Quinet P., Raymond J., 2009, ApJ, 701, 865
Kelly K. J., Ilidis C., Downen L., José J., Champagne A., 2013, ApJ, 777, 130
Langer W. D., Velusamy T., Pineda J. L., Willacy K., Goldsmith P. F., 2014, A&A, 561, A122
Liao J.-Y., Zhang S.-N., Yao Y., 2013, ApJ, 774, 116
Luo Y., Fang T., 2014, ApJ, 780, 170
Ness J.-U., et al., 2003, ApJ, 594, L127
Ness J.-U., et al., 2007, ApJ, 665, 1334
Ness J.-U., et al., 2009, AJ, 137, 3414
Ness J. U., 2012, Bulletin of the Astronomical Society of India, 40, 353
Ness J.-U., et al., 2013, A&A, 559, A50
Nicastro F., Senatore F., Gupta A., Guinainzzi M., Mathur S., Krongold Y., Elvis M., Piro L., 2016a, MNRAS, 457, 676
Nicastro F., Senatore F., Gupta A., Mathur S., Krongold Y., Elvis M., Piro L., 2016b, MNRAS, 458, L123
Okada Y., et al., 2013, A&A, 553, A2
Orio M., 2012, Bulletin of the Astronomical Society of India, 40, 333
Orio M., et al., 2013, MNRAS, 429, 1342
Pezat A., Hauschildt P. H., Ness J.-U., Starrfield S., 2005, A&A, 431, 321
Pineda J. L., Langer W. D., Velusamy T., Goldsmith P. F., 2013, A&A, 554, A103
Pineda J. L., Langer W. D., Goldsmith P. F., 2014, A&A, 570, A121
Pineda J. L., et al., 2017, ApJ, 839, 107
Pinto C., Kaastra J. S., Costantini E., Verbunt F., 2010, A&A, 521, A79
Pinto C., Kaastra J. S., Costantini E., de Vries C., 2013, A&A, 557, A25
Rauch T., 2016, in Deustua S., Allam S., Tucker D., Smith J. A., Richter P., et al., 2017, A&A, 607, A48
Rauch T., 2016, in Deustua S., Allam S., Tucker D., Smith J. A., Richter P., et al., 2017, A&A, 607, A48
Rauch T., 2016, in Deustua S., Allam S., Tucker D., Smith J. A., Richter P., et al., 2017, A&A, 607, A48
Petz A., Hauschildt P. H., Ness J.-U., Starrfield S., 2005, A&A, 431, 321
Pineda J. L., Langer W. D., Velusamy T., Goldsmith P. F., 2013, A&A, 554, A103
Pineda J. L., Langer W. D., Goldsmith P. F., 2014, A&A, 570, A121
Pineda J. L., et al., 2017, ApJ, 839, 107
Pinto C., Kaastra J. S., Costantini E., Verbunt F., 2010, A&A, 521, A79
Pinto C., Kaastra J. S., Costantini E., de Vries C., 2013, A&A, 557, A25
Rauch T., 2016, in Deustua S., Allam S., Tucker D., Smith J. A., Richter P., et al., 2017, A&A, 607, A48
Robin A. C., Reylé C., Derrière S., Piccard S., 2003, A&A, 409, 523
Savage B. D., et al., 2017, ApJS, 232, 25
Schull N. S., Corrales L., Canizares C. R., 2016, ApJ, 827, 49
Schwarz G. J., et al., 2011, ApJS, 197, 31
Shannon M. J., Peeters E., Cami J., Blommaert J. A. D. L., 2018, ApJS, 551, A25
T. M., Palmeri P., Quinet P., Raymond J., 2009, ApJ, 717, 363
Richter P., et al., 2017, A&A, 607, A48
Rabin A. C., Reylé C., Derrière S., Piccard S., 2003, A&A, 409, 523
Savage B. D., et al., 2017, ApJS, 232, 25
Schull N. S., Corrales L., Canizares C. R., 2016, ApJ, 827, 49
Schwarz G. J., et al., 2011, ApJS, 197, 31
Shannon M. J., Peeters E., Cami J., Blommaert J. A. D. L., 2018, ApJ, 855, 32
Ueda Y., Mitsuda K., Murakami H., Matsumita K., 2005, ApJ, 620, 274
Welty D. E., Lauroesch J. T., Wong T., York D. G., 2016, ApJ, 821, 118
Yao Y., Schulz N. S., Gu M. F., Nowak M. A., Canizares C. R., 2009, ApJ, 696, 1418
van Rossum D. R., 2012, ApJ, 756, 43

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