Line Identification and Excitation of Autoionizing States in a Late-type, Low-mass Wolf–Rayet Star

Robert Williams1,2, Catherine Manea3, Bruce Margon2, and Nidia Morrell4
1Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; wms@stsci.edu
2Department of Astronomy & Astrophysics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
3Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA
4Las Campanas Observatory, Carnegie Observatories, Casilla 601, La Serena, Chile

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Abstract

Identifications of a large fraction of previously unidentified lines in the complex spectrum of the low mass, late-type LMC [WC11] star J060819.93−715737.4 have been made utilizing electronic databases. There are an exceptionally large number of C II emission lines originating from autoionizing (AI) levels. Resonance fluorescence between the C II ground state and excited AI levels is shown to be an important photoabsorption process that is competitive with dielectronic recombination in exciting AI emission lines in stellar winds, and has broad application to many types of emission-line stars. In addition, numerous C II quartet multiplets appear in emission that are not excited directly by recombination or resonance fluorescence, signifying high wind densities in the emission region that enhance collisional transfer between doublet and quartet states.

Unified Astronomy Thesaurus concepts: WC stars (1793); Stellar spectral lines (1630)

Supporting material: data behind figure, machine-readable table

1. Introduction

The spectra of diffuse objects of low density, including planetary nebulae, old supernova remnants, and H II regions, are dominated by emission lines with strong forbidden transitions that differ significantly from those formed in the higher-density emitting regions that characterize stellar winds. Many of the differences are due to the large disparity in density between the different classes of objects that dictates which types of transitions can be prominent. However, a more important cause of the dissimilar spectra is the large difference in the dilution of the stellar continuum that drives the ionization and thermal balances in the objects. Fluorescence of stellar continuum radiation by line absorption plays at most a minor role in the population of excited levels in diffuse nebulae. However in stellar winds that originate near the photosphere it is a process that excites the emission-line spectrum.

The recent study of the late-type LMC [WC11] Wolf–Rayet star J060819.93−715737.4 (hereafter, J0608) by Margon et al. (2020a; hereafter, Paper I) illustrates what is involved in interpreting the visible spectrum of an object whose emission is formed in a stellar wind. The observed J0608 spectrum, shown in Figure 1, consists of emission and absorption lines formed from multiple ions. The emission lines are predominantly C II and He I transitions, whereas the absorption features are primarily due to Ne II and O II. Other low-mass, late-type Wolf-Rayet stars, denoted [WC] stars, including the prototype CPD −56° 8032 (De Marco et al. 1997), display similarly unusual spectra. The strongest emission lines in J0608 were identified in Paper I, but a more detailed effort to identify a large number of weaker features, most of whom have not been cataloged previously for this type of object, was deferred. We report here our more extensive effort to identify observed lines with specific transitions for which laboratory data exist and that may be considered astrophysically reasonable for a late-type [WC] star with a prominent wind.

It should be noted that a number of the emission features observed in J0608 were identified in Paper I as originating from autoionizing (hereafter, AI) levels above the ionization continuum, yet many of these transitions are not listed in authoritative databases such as the NIST Atomic Spectra Database5 or CHIANTI.6 Their identifications rely on a database making use of the important laboratory measurements of energy levels made by the Van de Graaff generator work by Bashkin & Stoner (1975, 1978). The existence of a multitude of transitions satisfying Russell–Saunders LS- and intermediate coupling rules has been gathered from these experimental data, yielding accurate wavelengths, and many such transitions have been listed in the v.2.05 Atomic Line List7 electronic database of van Hoof (2018). This database lists many transitions not found in other databases and serves as an important resource for the identification of lines from atomic species observed in astronomical spectra.

2. New Line Identifications

Following the publication of our initial results for J0608 we undertook a more thorough effort to identify transitions for which line identifications (IDs) were not made in Paper I. Using the best signal/noise spectrum we have of J0608, observed with the Magellan MagE spectrograph on 2019 May 3, we re-measured line wavelengths for individual, relatively unblended features for which no satisfactory ID had been assigned in Paper I. Multiple databases were queried to find candidate transitions that were deemed reasonable based on multiple considerations. The usual factors of wavelength agreement, presence/absence of other members of the same multiplet, line width, ionization level, ion abundance, and oscillator strength when known were taken into consideration.

5 https://www.nist.gov/pml/atomic-spectra-database
6 https://chiantidatabase.org/
7 http://www.pa.uky.edu/~peter/newpage/
in assigning an identification. We have succeeded in making what we believe to be satisfactory line IDs for almost 150 additional lines that had not been assigned IDs in Paper I. All of the emission features that we consider to be real, based on their appearance in both the 2017 December 30 and 2019 May 3 spectra, are listed in Table 1. A small number of emission lines remain without satisfactory ID in spite of our efforts, and these are also listed.

Each of the lines in Table 1 is identified by its laboratory air wavelength to 0.1 Å and the spectroscopic terms of its lower and upper levels for its multiplet. Individual j-states are not denoted because in numerous cases individual multiplet
members are not resolved in our spectrum. Thus, various emission features consist of multiple transitions within an unresolved multiplet. With the exception of some of the emission lines originating from AI levels, the listed wavelength and spectroscopic terms are sufficient to identify each transition specifically, virtually all of which appear in the NIST database. For emission lines originating from AI levels, we provide in Table 1 the electronic configurations of the lower and upper levels, which are sufficient to identify each transition—all of which appear in Bashkin & Stoner (1975) and the van Hoof (2018) v2.05 Line List. The upper and lower levels of all C II/Al transitions identified in Table 1 have a 1s2s2p6(1P) core term.

Several reasons factor into why the ID of a given feature is unassigned. Lack of proper wavelength agreement is a primary consideration that introduces uncertainty in features that clearly consist of multiple transitions. Absence of a transition in the databases is also a factor, normally resulting from either the lack of experimental data or inadequate theoretical calculations characterizing the transition. This is particularly true for AI levels more than a few eV above the ionization continuum. In some cases there are multiple transitions that are reasonable IDs and it is difficult to determine which of them are the proper ID, even after taking into account the presence or absence of associated multiplet members.

Several of the IDs in Table 1 are worthy of comment, especially the transitions generally associated with low-density nebular gas. The forbidden [O II] λ3727 doublet is prominent, as are the [S II] λ6717/34, [N II] λ6548/84, and [O I] λ6300/63 doublet that are not expected to arise in a stellar wind. As noted in Paper I, the known Galactic late-type [WC] stars are surrounded by planetary nebulae (PNe). Although none has been detected in images of J0608, the presence of the above nebular lines in its spectrum does indicate the likely existence of what could be a low surface brightness PN ejected by the object at an earlier epoch. Marson et al. (2020b) have noted that at the LMC distance, a PN of physical extent and surface brightness similar to that seen in the prototype Galactic [WC11] star CPD −56° 8032 would not be resolved in ground-based images.

The subjective judgment of what one considers astrophysical reasonableness certainly introduces its own bias. It is possible that some of the unassigned transitions in Table 1 of this paper and Table 1 of Paper I are indeed listed in databases but lacking information on expected associated lines, thus resulting in uncertainty for an otherwise valid ID so that it is rejected.

3. Excitation of Autoionization States

The interesting mixture of numerous C II emission lines in the J0608 spectrum with Ne II and O II absorption lines was described in Paper I. One feature of the spectrum discussed in that paper is the significance of multiple strong C II emission lines originating from Al levels. De Marco et al. (1997) had previously called attention to the presence of such transitions in the low-mass [WC10] stars CPD-56° 8032 and He 2-113, and they considered the different processes that produce the emission from Al levels. Al transitions were also noted in the spectrum of V348 Sgr (Dahari & Osterbrock 1984; Leuenhagen et al. 1994), which although classified as a hot R CrB star (Crowther et al. 1998), does share characteristics of the late [WC] class. The presence of numerous transitions between Al levels in J0608 does suggest that they may be a characteristic of winds with enhanced carbon abundance.

The mechanism that populates Al levels is generally acknowledged to be dielectronic recombination (DR; Seaton & Storey 1976; Nussbaumer & Storey 1984; Pradhan & Nahar 2011). Using the CPD-56° 8032 spectrum, De Marco et al. (1997) performed a detailed study of its formation and the relative intensities of the emission lines. Their analysis, which included Al doublet transitions, used fits to the profiles of individual members of AI multiplets to determine relative optical depths and accurate line fluxes for the lines. They found C II excited bound–bound transitions, including Al doublets and strong radiative recombination lines like λ4267, to be optically thick in the CPD-56° 8032 wind. Their model, which neglected absorption of the stellar continuum by lines, did demonstrate that many line optical depths can be sufficiently large that this needs to be accounted for when determining physical conditions and element abundances.

Al levels are doubly-excited states and photoexcitation of an ion in the ground state does not normally produce excitation to an Al level because the cross sections for radiative excitation are larger for both singly-excited bound states and for photoionization. There are exceptions, however. Absorption of a photon with ionization energy by an electron in the outer shell, but of the inner sub-shell of the valence shell, can result in excitation of the inner sub-shell electron to a bound Al level. This produces a doubly-excited Al state, and it is possible for the absorption to occur via electric dipole transitions obeying LS-coupling selection rules with high transition probabilities. Such absorptions, which are frequently followed by auto-ionization, appear as prominent resonances in the photoionization cross sections of ions (Pradhan & Nahar 2011).

The above photoexcitation mechanism was suggested in Paper I as a possible cause for the numerous strong Al transitions in the J0608 spectrum. Their intensities originating from both C II doublet and quartet Al levels were shown to be more than an order of magnitude greater than can be accounted for by DR alone, assuming the lines to be optically thin. This is especially significant in understanding the population of C II quartet Al levels, which are not populated directly by DR from the C III singlet ground state via LS-coupling, thus suggesting collisional transfer between the doublet and quartet states. However, because the results of De Marco et al. (1997) have shown that the emission lines may not be optically thin as we
had assumed for simplicity, this matter needs to be pursued further.

Three processes can populate Al levels by the absorption of continuum radiation: (1) resonance-line absorption from the ground state to Al levels; (2) absorption from excited levels populated by optically thick resonance-line scattering, from which transitions to Al levels with large f-values exist (Dahari & Osterbrock 1984); and (3) a stellar continuum that is sufficiently strong to produce adequate photoexcitation. Absorption of stellar continuum radiation is not usually considered a significant process, however there are conditions where it could be relevant for C II in late [WC] stars like J0608 and contribute to observed Al line strengths.

The rate $R_j$ at which DR populates level $j$ of ion $i$ is given by

$$R_j = n_e n_{i+1} \alpha_{\text{DR}}(j) \text{cm}^{-3} \text{s}^{-1},$$

where $n_e$ and $n_{i+1}$ are the electron and ion number densities, and $\alpha_{\text{DR}}(j)$ is the DR coefficient for level $j$. DR coefficients have been calculated for numerous ions by Storey (1981), Nussbaumer & Storey (1984), and Sochi & Storey (2013), and are sensitive to electron temperature $T_e$ for Al levels with excitation potentials significantly above the ionization limit of ion $i$. However, they are insensitive to $T_e$ for levels whose excitation potentials are comparable to or less than the mean free-electron energy.

The rate $P_{ij}$ at which photoabsorptions from the ground state populate level $j$ of ion $i$ is

$$P_{ij} = n_i B_{ij} J_{ij} \text{cm}^{-3} \text{s}^{-1},$$

where $B_{ij}$ is the Einstein stimulated emission coefficient for the transition and $J_{ij}$ the mean intensity of radiation from the star + wind continuum at the resonance-line frequency $\nu_{ij}$. The relative abundance of C$^+$ and C$^{+2}$ ions is determined by the ionization equation

$$n_{\text{C}} = \int_{h\nu}^{\infty} 4\pi J_0 \alpha_{\nu} d\nu = n_e n_{\text{C}^{+2}} \alpha^{\text{res}}(T_e),$$

where $\nu_c$, $\alpha_\nu$, and $\alpha^{\text{res}}(T_e)$ are the ionization frequency threshold, photoionization cross section, and total radiative recombination coefficient, respectively, for C$^+$.

For the wavelength regime relevant for the carbon ions present in the J0608 spectrum we represent the continuum radiation field by the Wien approximation due to J0608’s relatively low photospheric temperature of $T_\star < 30,000$ K, estimated from the spectral energy distribution, which causes the maximum blackbody radiation to remain longward of 1000 Å. Given the steep decline in the continuum flux at higher frequencies, the photoionization cross section for C II can be approximated well by $a_\nu = a_\nu \times (\nu_c/\nu)^2$, with $a_\nu = 4.6 \times 10^{-18}$ cm$^{-2}$ (Nahar & Pradhan 1997). Taking $J_\nu = J_c \times (\nu/\nu_c)^3 \exp(-h\nu/kT_\star)$, Equation (3) leads to

$$n_{\text{C}^+} = n_e n_{\text{C}^{+2}} \times h\nu_c \alpha^{\text{res}}(T_e) / (4\pi J_c a_\nu kT_\star) \times \exp(h\nu_c/kT_\star).$$

Using the relationship between the transition oscillator strength and Einstein coefficient, $B_{ij} = 4\pi^2 \nu_{ij}^2 / (m_e c)$ (Mihalas 1978), the rate of excitations to a level $j$ by photoexcitation from the C II ground state, $P_{ij}$, becomes

$$P_{ij} = n_{\text{C}^+} \times 4\pi^2 \nu_{ij}^2 / (m_e c h \nu_{ij}) J_c (\nu_{ij}/\nu_c)^3 \exp(-h\nu_{ij}/kT_\star).$$

(5)

A comparison of the relative rate of photoexcitation to that of DR in populating a level $j$ is given by the ratio of the two rates,

$$P_{ij}/R_j = \pi h c \nu_{ij} / (m_e c a_\nu kT_\star) \times (\lambda_e/\lambda_{ij})^2 \times \alpha^{\text{res}}(T_e) / \alpha_{\text{DR}}(j) \times \exp(h(\nu_c - \nu_{ij})/kT_\star).$$

(6)

This relation can be applied to the excitation of the C II 2s2p$^2$3P$^o$ 2p state from both radiative and DR, as has been considered by Nahar (1995), and continuum photoexcitation via the 2s$^2$2p$^2$3S$^o$-2s2p$^3$P$^o$ $\lambda 466$ Å UV resonance line to the upper autoionization level. The DR coefficient for a level can be derived from the published emission coefficient by correcting for the autoionization probability for the level and the branching ratio for the transition. However, rather than determine the DR rate for individual C II Al levels we consider the more appropriate population rate for all Al levels collectively, $R_{Al}$, using the value of the DR rate for Al levels that has been calculated by Davey et al. (2000), $\alpha_{\text{DR}}(C^+) = 5 \times 10^{-12}$ cm$^3$ s$^{-1}$.

In determining the rate of photoexcitation from the ground state to the single Al level 2s$^2$2p$^2$3P$^o$ 2p due to the $\lambda 466$ Å resonance line, the photospheric temperature is taken to be $T_\star = 28,000$ K, the approximate determined value from Paper I. We also select the electron temperature $T_e = 10^{4}$ K for the calculation, with the atomic parameters $\alpha^{\text{res}}(C^+) = 6.0 \times 10^{-12}$ cm$^3$ s$^{-1}$ (Nahar 1995), $\lambda_{466} = 0.018$ (Kramida et al. 2018), and $\lambda_e = 508$ Å. Using these values the ratio of the continuum photoexcitation rate for the one resonance line to its upper Al level relative to the DR rate for all Al levels is $P_{ij}/R_{Al} = 0.10$. When additional resonance lines are considered, not to mention a higher value of $T_\star$ that would provide more UV photons, resonance-line absorption of continuum radiation is definitely a competitive process with DR in populating autoionization states. Similar values of the contribution of continuum absorption from excited bound to Al levels yield similar values of $P_{ij}/R_{Al}$. These figures demonstrate that the resonance fluorescence process should be taken into account when considering the excitation of Al transitions.

The question of how line optical depths influence the population of excited states remains to be understood, especially in relation to the excited levels that do not couple directly to the ground state via strong resonance lines, i.e., those that are allowed by LS-coupling. In the case of C II this is especially important for the quartet levels that are not reached directly by radiative recombination or DR from the C III singlet ground state nor by resonance-line scattering from the C II doublet ground state.

As is evident from Table 1, C II quartet emission lines that include a number originating from Al levels do appear with appreciable strength in J0608. For wind densities greater than $10^{12}$ cm$^{-3}$, collisional transfer between excited levels of every multiplicity that have similar excitation potentials will be a dominant process, just as it is for the O I triplets and quintets (Bhatia & Kastner 1995; Kastner & Bhatia 1995). It is very likely to be responsible for the population of many of the C II quartet states in J0608. Construction of a wind model for J0608 that considers known radiative and collisional processes is
surely one of the best ways to determine the significance of the different processes that produce the object’s spectrum. Based on the calculations above, in the future such models should take into account the fact that ground-state absorption is a viable process that must be considered in the population of AI levels.

4. Summary

The large majority of emission lines that appear in the spectrum of the [WC11] star J0608 have now been identified from information obtained in the NIST and V2.05 Atomic Line Lists. The relatively narrow line widths of ∼90 km s⁻¹ FWHM for this type of object have enabled most multiplets to be resolved, aiding in their ID. However, the large number of candidate transitions that occur within the acceptable wavelength interval for most of the observed lines does cause sufficient uncertainty that inevitable errors in ID will occur.

The emission spectrum contains an unusually large number of transitions originating from C II AI levels. We have shown that resonance fluorescence from the ground state can play a prominent role in populating AI levels. Uncertainties in the J0608 wind properties do not allow a more definite statement to be made as to which processes dominate the excitation of a given level without the aid of a model that treats radiative transfer in the wind. Such models do exist, e.g., CMFGEN developed by D. J. Hillier and colleagues (Hillier & Miller 1998; Hillier & Lanz 2001) is one example, and would be very useful in confirming those physical processes that play a role in the formation of spectra of late [WC] and R CrB stars.

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Appendix

Possible Rydberg Enhanced Recombination

A recent study by Nemier et al. (2019) has called attention to a process called Rydberg Enhanced Recombination (RER) that can be important in populating bound states just below the ionization threshold. It enhances the emission by radiative decay from highly excited bound levels but has little effect in augmenting excitation of AI levels. There is a test to determine the relative importance of cascades from AI levels versus the RER process in populating bound levels near the ionization limit. It is a comparison of the relative intensities of the “feed” transitions from AI levels into a highly bound level compared to the intensities of the emission lines out of that level.

The high bound level of C II 2s2p3d ⁴F° is the upper level of the λ7118 ⁴D⁻⁴F° multiplet transition. Because of its close proximity within 0.1 eV of the C⁺ ionization limit that level is a good candidate for enhanced population by RER. The level is also populated radiatively by cascades from the C II λ3877 and λ5258 multiplets, whose upper levels are AI states that directly feed the λ7118 emission feature. When the λ3877 + λ5258 multiplet fluxes are similar to or exceed the flux of λ7118, it indicates that cascades from the AI levels may be the predominant source of excitation of the 3d ⁴F° level. Our measurements from the 2019 May 3 MagE spectrum yield an observed flux ratio of F(λ3877+λ5258)/F(λ7118) ∼ 2.3, not accounting for probable modest reddening that decreases the true ratio. Thus, radiative cascading from AI levels into the 3d ⁴F° upper level of λ7118 should lead to it having a higher intensity than observed unless a non-radiative de-excitation of that level is also taking place, e.g., collisional transfer to other states. Under these circumstances, there is no substantive evidence that RER contributes to the population of the 3d ⁴F° state in J0608.

ORCID iDs

Robert Williams https://orcid.org/0000-0002-3742-8460
Bruce Margon https://orcid.org/0000-0002-7837-3363
Nidia Morrell https://orcid.org/0000-0003-2535-3091

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