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The discrepant kinematics of ORLs and CELs in NGC 7009 as a function of ionization structure

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Abstract. We study spatially- and velocity-resolved echelle spectroscopy of NGC 7009 taken with with the UVES spectrograph at the European Southern Observatory's Very Large Telescope. We aim to determine whether the kinematics of recombination and collisionally-excited emission lines may reveal any differences that might help explain the well-known abundance discrepancy found in H ii regions and planetary nebulae. We find a plasma component that emits in recombination lines of C ii, N ii, O ii, and Ne ii with discrepant kinematics: These lines have unexpectedly similar kinematics that is discrepant from the ionization structure derived from other evidence. The kinematics of the C ii, N ii, O ii, and Ne ii lines does not coincide with that of the [O iii] and [Ne iii] collisionally-excited lines. The simplest explanation is that an additional plasma component exists in NGC 7009, occupying a volume different from and interior to that which emits the [O iii] and [Ne iii] lines, and emitting in recombination lines of C ii, N ii, O ii, and Ne ii. Full details may be found in Richer et al. (2013).

Key words. cosmological parameters — Galaxies: abundances — ISM: abundances — ISM: kinematics and dynamics — planetary nebulae: NGC 7009

1. Introduction

Emission lines are commonly used to infer chemical abundances of C, N, O, Ne, S, Cl, and Ar, in ionized plasmas throughout the universe. Normally, the bright collisionally-excited (forbidden) emission lines that are used. However, at least in nearby objects, the much fainter recombination lines of C, N, O, and Ne may also be used (e.g., Aller 1984; Osterbrock 1989). The chemical abundances inferred from both methods have been compared frequently and it is almost always found that the abundances inferred from recombination lines are greater than those inferred from collisionally-excited lines (e.g., Wyse 1942; Liu 2010), leading to what is known as the abundance discrepancy (for recent reviews, see Peimbert & Peimbert 2006; Liu 2006, 2010; Bohigas 2009).

The abundance discrepancy exists in both H ii regions and planetary nebulae. In H ii regions, the abundance discrepancy is almost always a factor of two, i.e., the recombina-

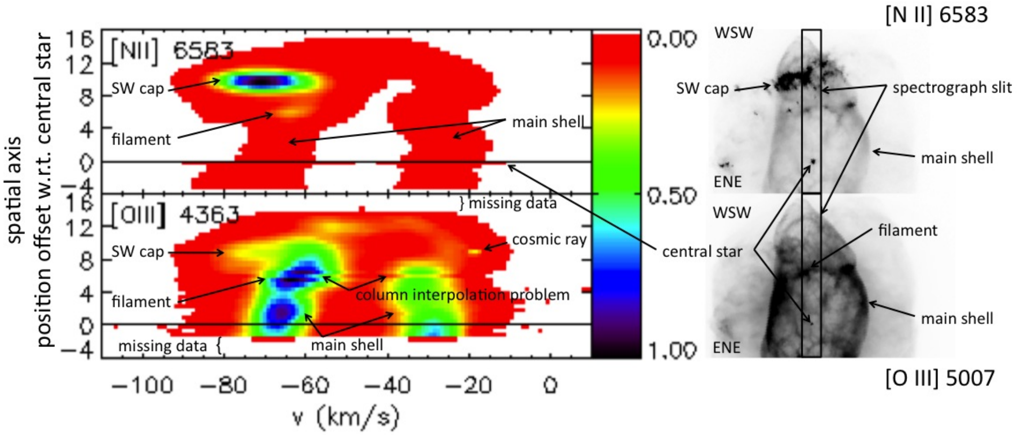

Fig. 1. The PV diagrams and images (HST/WFPC2) of NGC 7009 illustrate the correspondence between structural and kinematic features in the light of [N ii] λ6583 and [O iii] λ4363,5007. In the PV diagrams, the spatial direction corresponds to the vertical axis while the spectral/velocity direction corresponds to the horizontal axis. Comparing the PV diagrams and images from each ion, it is easy to identify the kinematics of individual structural elements, such as the SW cap and filament, both of which are on the side of the object approaching Earth, or the main shell, which constitutes the dominant structure of NGC 7009 (covering all spatial positions).

tion lines imply abundances twice those implied by the collisionally-excited lines (e.g., García-Rojas & Esteban 2007). In planetary nebulae, the same result is the most common, but about 20% have abundance discrepancies exceeding a factor of five. The abundance discrepancies for C, N, O, and Ne are usually similar, leaving abundance ratios, such as O/Ne unaffected by the choice of lines used (e.g., Liu 2010). Historically, the explanation of these discrepant abundances has focussed upon the temperatures used to derive them, since the intensities of recombination lines and collisionally-excited lines depend differently upon the temperature, having power law and exponential behaviors, respectively (Peimbert 1967). More recently, both physical processes and issues related to the object structure have been considered (Liu et al. 2000; Garnett & Dinerstein 2001; Mesa-Delgado et al. 2008; Rodríguez & García-Rojas 2010; Pradhan et al. 2011; Tsamis et al. 2011; Nicholls et al. 2012; Bilíková et al. 2012).

2. Internal kinematics in NGC 7009

Thus far, little use has been made of the kinematics of recombination and collisionally-excited lines, though its potential is significant (e.g., Sharpee et al. 2004). If the two types of lines arise from the same plasma component, the kinematics of both types of lines will be similar. If the two types of lines have different kinematics, it might suggest that certain proposed solutions to explain the abundance discrepancy are not viable.

We use spectra for NGC 7009 drawn from the European Southern Observatory data archive, obtained on 2002 August 4 using the UV-Visual Echelle Spectrograph on the Very Large Telescope UT2/Kuyen, program ID 69.D-0413(A) and 60.A-9022(A). From these spectra, we construct position-velocity (PV) diagrams that allow us to study the internal kinematics within NGC 7009 as a function of position along the spectrograph slit. Fig. 1 presents an annotated example of a PV dia-

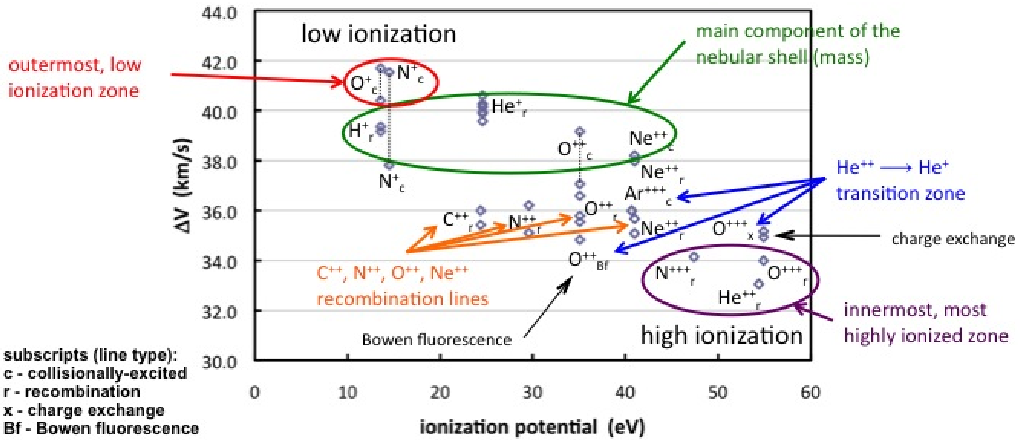

Fig. 2. We plot the line splitting for each emission line considered as a function of the ionization potential of the ion. As expected, emission lines from more highly ionized states arise from more internal zones of the nebula with smaller line splitting (the inner material cannot overrun material external to it). The *only* exception to this rule is the kinematics of the C II, N II, O II, and Ne II lines: at least O II and Ne II should arise from the same zone giving rise to the [O III] and [Ne III], and C II and N II could have even larger velocity splitting.

gram, illustrating the images and spectra in different emission lines at the same spatial scale.

We characterize the kinematics of these PV diagrams by computing the velocity splitting between the approaching and receding sides of the main shell (see Fig. 1). We plot the velocity splitting for each ion as a function of the ion's ionization potential in Fig. 2. We find different velocity splitting for ions in different zones of the nebula with clear velocity changes between them: the He^{++} zone, the $He^{++} \rightarrow He^{+}$ transition zone, the ions dominating the mass of the nebular shell, and the N^{+}/O^{+} zone. As expected, the main trend is from low velocity splitting for the lines of the most highly ionized ions to a large velocity splitting for the lines from the most lowly ionized ions. The *only* unexpected result is that the velocity splitting of the C II, N II, O II, and Ne II recombination lines does not coincide with that for the [O III] and [Ne III] collisionally-excited lines.

Fig. 3 emphasizes two issues. First, the PV diagrams of the C II, N II, O II, and Ne II recombination lines are all very similar. These recombination lines should arise primarily from the zone where C^{+}, N^{+}, O^{+}, and Ne^{+} are the second most abundant ionization stage. Second, the photoionization model indicates that the zone where C^{+} and N^{+} are the second most abundant ionization stage differs from the zone where O^{+} and Ne^{+} are the second most abundant ionization stage (colored arrows). Therefore, we do not necessarily expect kinematics so similar as observed.

Therefore, there are really two problems: First, ionization equilibrium should locate the emission from the O II/[O III] and Ne II/[Ne III] lines at the same velocities, since they arise from the same parent ions, O^{++} and Ne^{++}, respectively, and in the nebular zone where O^{+} and Ne^{+} are the second most abundant ionization stage. Second, in view of the gradient in the velocity splitting from Fig. 1, we do not necessarily expect the kinematics of the C II and N II lines to be so similar to that for the O II and Ne II recombination lines. Returning to Fig. 2, there is excess emission from the O II and Ne II recombination lines that cannot be explained by the plasma emitting in the [O III] and [Ne III] collisionally-excited lines. The simplest solution is that there is a second plasma component emitting in the O II and Ne II recombination lines interior to the zone from which most of the emission from the [O III] and

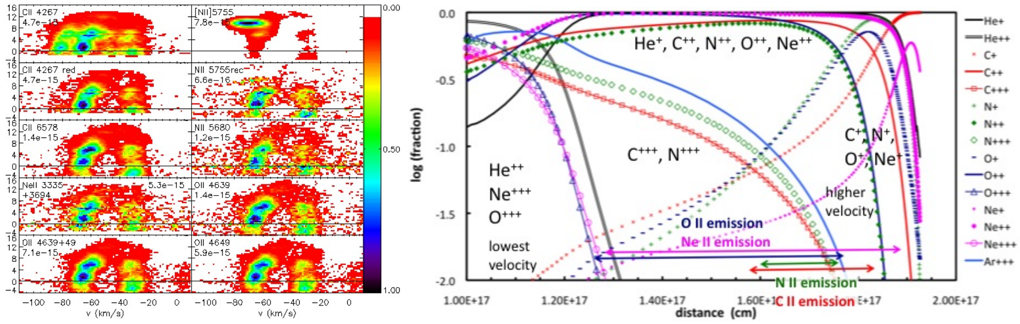

Fig. 3. We present the PV diagrams for a variety of C II, N ii, O ii, and Ne ii recombination lines (left panel) and the ionization fractions for different ions in a simple photoionization model (right panel; v08.00 of CLOUDY, last described by Ferland et al. 2013). The PV diagrams emphasize the similarity of the kinematics of the emission arising from recombination lines. The photoinization model clearly indicates that the emission from C II and N ii arises from a different zone from the emission from O ii and Ne ii.

[Ne iii] collisionally-excited lines arises. Given the ionization structure expected, the same is likely true for the emission from C ii and N ii. Thus, there would appear to exist a second plasma component in NGC 7009 that emits in the O ii and Ne ii recombination lines (and very likely those of C ii and N ii as well).

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