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Atomic data for and from the analysis of gaseous nebulae

ABSTRACT

The need for cross-checks between observations of emission line strengths in gaseous nebulae, and theoretical predictions of transition probabilities and collision strengths for forbidden lines is discussed. Observed line ratios of transitions in the ions N^+, O^{+2} and S^+ are compared with theoretical predictions. It is concluded that inconsistencies are apparent, which need to be resolved in order to achieve the accuracies in derived astrophysical data that can be expected from modern observational techniques and calculations of atomic data.

INTRODUCTION

Substantial improvements in accuracy have been made over the last decade in both, the observational determination of emission line ratios in gaseous nebulae, and in theoretical computations of transition probabilities and collision strengths for the ions of interest. In addition observations can now be compared with detailed models of H II regions treating the radiative transfer in the presence of inhomogeneities and dust (Mathis 1982).

As a result, the fine analysis of real objects in terms of chemical abundances and of the energy distribution in the ionizing source becomes feasible on the 10% accuracy level for an increasing number of objects. This opens up new ways to investigate elemental abundance variations in galaxies within and between H II regions, rather than on kpc scales. This will have impacts on our understanding of the history of star formation and chemical evolution. The access to the otherwise unobservable FUV continua of hot stars will put constraints on input physics and parameters of stellar model atmospheres. Ions of particular interest in such studies are O^+, O^{+2}, S^+ and S^{+2} because they can be used profitably to map the the ionization structure without reference to total elemental abundances (Mathis 1982).

CONSISTENCY CHECKS

In order to achieve this goal, a close interaction between observations and theory is required. Observers in trying to approach higher accuracies on ever fainter lines need reliable theoretical predictions of line emissivities in order to cross-check the calibration procedures. On the other hand, theoretical predictions of forbidden line collision strengths and transition probabilities can only be tested against observations of real astronomical objects. What is required from time to time, are consistency checks similar to those of eg. Liller an Aller (1954), Seaton and Osterbrock (1957) and Saraph and Seaton (1970).

THE O^{+2} $\lambda\lambda$ 5007,4959 RATIO

The intensity ratio of these strong ^1D-^3P transitions in the $2p^2$ ground configuration of O^{+2} is essentially independent of T_e and n_e. It is the ratio of transition probabilities and energy differences, and could provide an ideal check on the linearity of detectors and on the external accuracy of the data analysis.

Theoretical predictions have remained almost unchanged, converging from an early value of 2.93 in 1951 to 2.89 $\pm$ 0.02 today. Liller and Aller (1954) obtained 3.03 $\pm$ 0.11 from photoelectric observations; at that time not in contradiction with theory. The analysis of more than 600 modern data, which takes into account detector non-linearities and blends with faint He I lines, leads to a most probable observed ratio of 3.03 with a formal 3σ uncertainty of 0.005. Theoretical predictions therefore are off by about 10%, at least a 10σ effect. A similar discrepancy exists for the iso-electronic ion N^+; 2.92 $\pm$ 0.03 predicted versus 3.06 $\pm$ 0.01 observed.

These discrepancies are significant. They are disturbing, because they are consistent in the iso-electronic sequence (i.e. not likely to be observational inaccuracies), and because prediction as well as observation have remained at essentially unchanged values, despite the several orders of magnitude improvements in input physics and observational techniques. As a user of atomic data one might ask the question: how large are the margins for more important line ratios in that sequence ?

THE PROBLEMATIC S^+ ION - ELECTRON DENSITIES

The S^+ ion plays a dominant role in plasma diagnostics for most of the observations of gaseous nebulae. The ''said to be'' density sensitive ^2D-^4S nebular type transitions are easily observed and resolved even in faint objects at low spectral resolution. Usually, they provide the only electron density estimator available in chemical abundance studies.

The comparison by Saraph and Seaton (1970) of densities obtained from several such n_e sensitive emission line ratios of O^+ and the iso-electronic ions S^+, Cl^{+2} and Ar^{+3} led to the conclusion, that corrections had to be applied (mainly to S^+ density values) in order to achieve consistency.

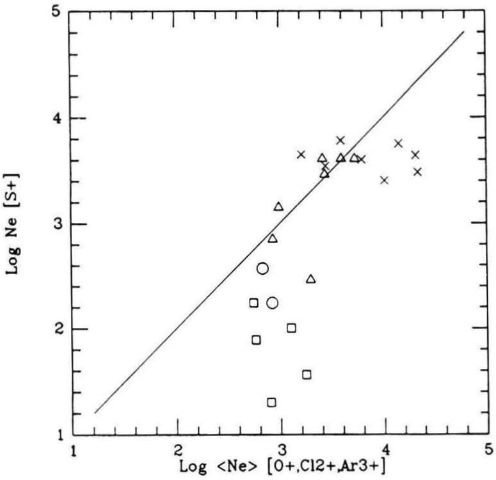

Fig. 1. Comparison of logarithmic densities derived from the S^+ ^2D-^4S transitions with averaged densities obtained from other ions.

Eissner and Zeippen (1981) resolved a long standing discrepancy between predicted and observed asymptotic densities for the O^+ ion (Seaton and Osterbrock 1957), later followed up along the $2p^3$ and $3p^3$ sequences, altering the transition probability sets. Also the new calculations of collision strengths for these sequences have led to significant changes (cf. Butler and Zeippen 1989 and references therein). How do these modern atomic data sets compare with new observations ?

In Fig. 1 logarithmic densities from the nebular S^+ ^2D-^4S transitions are compared with electron densities obtained from O^+, Cl^{+2} and Ar^{+3} (average if applicable) for the planetary nebulae (crosses) of Saraph and Seaton (1970), the Orion nebula (triangles), the 30 Doradus H II region (circles) and several other galactic and extragalactic nebulae (squares). S^+ density values are large underestimates almost everywhere in the diagram, especially in the low and high density regimes. In other words, observationally S^+ has only a very narrow density sensitive region. If this holds true, i.e. if something is amiss in the atomic data set of S^+, this would be particularly disturbing, because most of the electron densities obtained for extragalactic objects are based on S^+ observations. A direct consequence would be that filling factors have to be lowered by considerable amounts.

THE S^+ ION - MISSING INTERNAL CONSISTENCY

This seems not to be the only trouble with S^+. The ratio of the transauroral to nebular lines ($\lambda\lambda$ 6718 + 6731)/($\lambda\lambda$ 4069 + 4076) might be used to obtain T_e and n_e simultaneously for the same ion, a unique possibility. But determinations of either of the two parameters for a large sample of observations in low S^+ density objects are not in satisfactory agreement with values derived from plasma diagnostics of other ions.

In addition, the predicted line emissivity ratio of the two transauroral lines remains almost constant 3.0-3.2 over the T_e, n_e range covered by observational data. Yet, the available data are: 0.3-2.3 (giant H II regions), 2.1 (Orion nebula), 2.3 (Jupiter's plasma ring in the orbit of Io), and 0.9-7.5 (supernova remnants). There is a clear dependence of the observed ratio on T_e and n_e simultaneously.

It seems that the density sensitivity absent in the S^+ ^2D-^4S transitions is found again in the (^2D-^4S)/(^2P-^2D) emissivity ratio. Both sets, that of collision strengths and that of transition probabilities, seem to require improvements to reach consistency.

CONCLUSIONS

In summary it is comforting that the large set of atomic data available today for analysis of gaseous nebula spectra is consistent enough in general to show the presence of a few marked discrepancies. Earlier work on gaseous nebulae (cf. Saraph and Seaton (1970) or Pequinot et al (1978)) discussed differences found between plasma temperatures or densities determined from different ionic species, or problems in obtaining model nebulae consistent with observations in terms of real astrophysical effects (eg. density gradients, temperature structure) Although some of those interpretations might be valid, historically the development of the atomic data sets used has made most of those object related explanations obsolete.

While the small discrepancies between observation and prediction for the N^+ and O^{+2} ^1D-^3P transitions do not necessarily influence the astrophysical interpretation of the data, they might carry important information about atomic physics. On the other hand, a careful inspection of the S^+ ion, both from observations and from theoretical calculations, is highly desirable.

Besides the understanding in atomic physics to be gained from improved calculations, the astrophysical interpretation of nebular data depends strongly on accurate atomic data for this particular ion. Not only provide S^+ n_e estimates the sole source of this plasma parameter for a large majority of interesting astronomical objects. Reliable sulphur abundances require accurate collision strengths and transition probabilities for S^+, because S^+ is the second most abundant ionization stage in the bulk of gaseous nebulae. The continuation of the long standing, excellent interaction between atomic physics and observational astrophysics of gaseous nebulae should be fruitful for both sides in the areas discussed.

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