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RESUME

Les paramètres atomiques correspondant aux processus de population et de dépopulation des niveaux d'énergie responsables des raies d'émission de l'O VII ont été recalculés. Ils permettent de réévaluer les mesures de densité électronique dans les éruptions solaires ainsi que d'examiner le spectre d'un reste de supernova Puppis A. Le rapport anormal d'intensité observé pour Puppis A a donné lieu à un premier modèle basé sur un plasma thermique de haute température hors équilibre d'ionisation. Nous proposons un autre modèle basé sur la présence d'un faible pourcentage d'électrons très énergétiques dans un plasma thermique plus froid. Ce modèle explique le rapport d'intensité sans invoquer des écarts à l'équilibre d'ionisation.

ABSTRACT

We present a revised theory and atomic model for the line intensities emitted by O VII, taking into account all of the processes responsible for the emission. This is used to provide a revision of the density measurements made during solar flares, as well as in an attempt to understand the spectrum of the Puppis A supernova remnant. In order to explain the strange intensity ratios observed from Puppis A, previous authors have proposed an interpretation based upon a high temperature thermal plasma ($>5\ 10^6$ K), in a non-equilibrium ionisation state. We present here an alternative model, based upon the assumed presence of a proportion of fast non-thermal electrons imbedded in an otherwise thermal plasma at a temperature of below $1\ 10^6$ K. This can adequately explain the observations, without the necessity of invoking departures from ionisation balance.

ATOMIC THEORY AND MODELLING.

Oxygen is amongst the more abundant elements to be found in the universe, and as such gives rise to many prominent spectra observed in astrophysical sources. At higher temperatures in the region of one million degrees, or greater, the helium-like ion stage O VII becomes prominent, and gives rise to a characteristic group of three strong lines; $1s^2\ ^1S - 1s2p\ ^1P$ (21.6 Å), $1s^2\ ^1S - 1s2p\ ^3P$ (21.8 Å), and $1s^2\ ^1S - 1s2s\ ^3S$ (22.1 Å), usually referred to as the resonance (R), intercombination (I) and forbidden (F) lines. The intensity ratios between these lines can be used as a diagnostic for electron density, temperature, and as we show here, for some other plasma parameters. Oxygen with Z = 8 remains close to the limit of LS coupling. All of the data necessary to calculate the line intensities (with the exception of the intersystem line transition probabilities) can be adequately calculated on the basis of LS coupling.

An attempt has been made to include in the model a more complete set of processes than hitherto, involving all mechanisms which effectively contribute to the intensity of the three lines observed. In many cases the mechanisms themselves have been recalculated to give more reliable rates. The following is a list of the processes included.

Direct Electron Impact Excitation. This uses the same method described by Bely-Dubau et al [1] for O VI states, and involves the Distorted Wave Approximation [2].

Resonance contributions of the type 1,2,n. The method employed can be found described by Steenman-Clark and Faucher [3].

Resonance contributions of the type 1,3,n. These follow the method described by Faucher and Dubau [4].

Cascades from higher n states. This follows the same method used by Bely-Dubau et al [5], in which the large number of excitation rates required are obtained using the collision strengths calculated by Sampson, Parks and Clark [6].

The ionisation balance theory used is that described by Arnaud and Rothenflug [7]. For the cases involving additional non-thermal electrons, this has been modified, using the increase in ionisation rate predicted by the theory of Lotz [8].

The contribution to the intensities of the three n = 2 transitions in O VII due to cascade following recombination from oxygen VIII has been included, both for radiative and dielectronic recombination. The method used is that described by Bely-Dubau et al [5].

Direct excitation of the O VII lines by inner-shell ionisation of O VI has been included, using the theory of Lotz [8].

Step-wise excitation has been incorporated for the only transition of importance at moderate densities, ie the $1s2s\ ^3S$ - $1s2p\ ^3P$ transition. This transition, calculated using the Distorted Wave Approximation [2], is responsible for the density dependance observed for the line ratios, at densities in excess of 10^9 cm^{-3}.

Direct excitation of the lines by fast electrons has been included, using the Distorted Wave Approximation [2]. The overall effect of a small percentage of fast electrons arises in part from this effect, and in part from the change in ionisation balance caused by the fast electrons.

OBSERVATIONS AND INTERPRETATION.

Solar Active Regions.

Freeman et al [9] in 1971 examined a range of observed intensity ratios then available. The density-dependent ratio $R = F/I$ was found to vary from 3.6, consistent with the then estimated low-density limit, to 1.9. These variations were assumed to be the result of higher densities which were deduced to be of the order 3 10^9 cm^{-3}, again based upon the then available theory. It now seems clear that the intensity errors in the available published observations were larger than claimed, and that all of these observations were probably close to the low-density limit. Gabriel and Jordan [10] using the same data set were also able to measure the value for the line ratio $G = (I+F)/R$ of 1.1, which is independent of density.

A more recent analysis of the same problem has been carried out by Mckenzie and Landecker [11], using active region spectra obtained from the P78-1 satellite. They confirmed that the regions observed were below the low density limit. They measured a value for R_0 of between 3.7 and 4.1, in agreement with calculations of Pradhan and Shull [12] of 3.95.

Solar Flares.

At the higher densities existing in solar flare plasmas, it is possible to obtain real and significant variations in the ratio R, thus enabling the measurement of intrinsic electron densities. Figure 1 shows data from the spectrometer SOLEX-A on the satellite P78-1. McKenzie et al [13] have interpreted the measured values of R, which were found to fall from 2.2 to 0.9 during the time of build-up of the flare. Using the 1972 atomic data from Gabriel and Jordan [14], they deduced a rise in electron density from 0.5 to 1.8 x 10^{11} cm^{-3}. Whilst it is clear that they have indeed measured densities of this order, it is necessary to use more accurate atomic theory in order to recalibrate this observation.

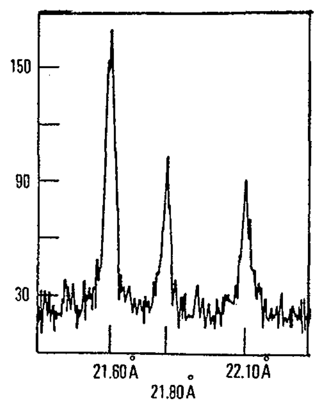

Figure 1. Oxygen VII spectrum from a solar flare [13].

This present theory gives values of density normally 0.71% of those quoted by McKenzie et al [13] using the data of Gabriel and Jordan [14], with a further small dependence on the assumed temperature.

Figure 2 shows the variation of the ratio R with density and temperature for a range of values important in the sun. In addition to a sensitivity to density which increases at higher densities, there is also a small sensitivity to the temperature. When measuring densities, this temperature sensitivity is unimportant at high densities, but when the density is close to the low-density limit of sensitivity, a more precise evaluation of the assumed temperature is required.

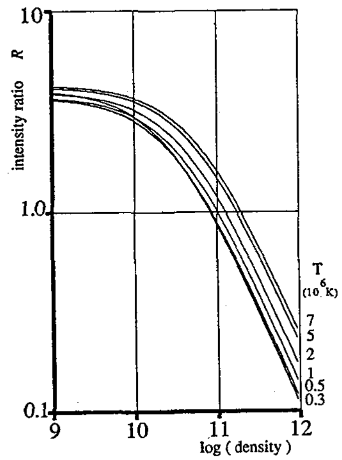

Figure 2. The line intensity ratio Forbidden / Intercombination, as a function of density and temperature.

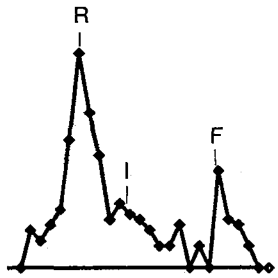

Figure 3. Oxygen VII spectrum recorded by the satellite Einstein from the Puppis-A supernova remnant [15] .

Puppis A

For non-solar sources, very little data is available, of sufficient resolution and quality to separate the three components of the oxygen VII line complex. In fact the only usable spectrum is the one of the Puppis A supernova remnant, recorded with the Focal Plane Crystal Spectrometer (FPCS) on the *Einstein* Observatory [15]. Since this instrument ceased functioning subsequently, and there is unlikely to be a comparable mission in orbit for a decade or more, the Puppis-A data set represents a unique observation in this domain.

In figure 3 we show the wavelength region covering the oxygen VII lines. The data are not of sufficient quality to derive a meaningful value for the ratio R (= F/I). However it is possible to measure the value of G = (I + F)/R, within certain error limits. The value obtained for the reciprocal, $1/G$ is 3.1, with limits between 2.1 and 5.0. Since most theoretical and observational values are close to 1.0, these observations pose a problem in interpretation. Canizares et al [16] have examined this problem, and shown that these line ratios can only be reached at temperatures between 5 and 10 10^6 K. Such temperatures are much higher than that required to produce the ion stage O VII in the steady-state. They infer that the remnant is not in equilibrium but in a state of transient ionisation at these temperatures.

Figure 4 shows the results of the present calculations for a plasma in ionisation equilibrium containing a small proportion of fast non-thermal electrons (here assumed to be of 20 keV energy, a value not critical for the modelling). The solid curves are for constant line ratio $1/G$ plotted as a function of temperature and of non-thermal electron proportion. The region consistent with the observed ratios is indicated in light shading. A further constraint is obtained from the requirement that the overall efficiency of emitting the lines (expressed as an effective excitation rate coefficient) must be greater than 3 10^{-13} cm^3 s^{-1}. This arises from consideration of the observed absolute intensity of the spectrum, and the deduced emission measure of the source, based upon other types of observation. This second constraint limits the permitted region to that shown in heavy shading.

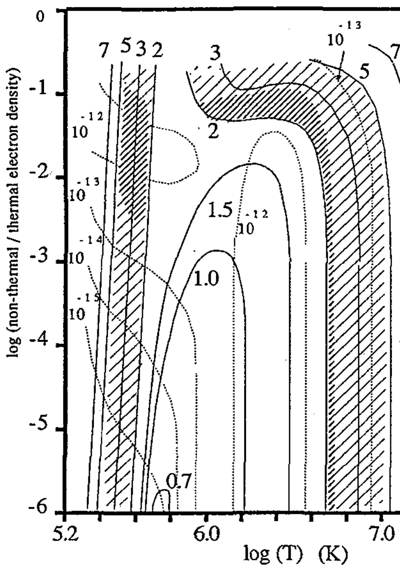

Figure 4. The intensity ratio 1/G (solid lines) and the effective collision rate coefficient W (dotted lines) (in cm^3 s^{-1}), as functions of temperature and non-thermal electron component. The heavy shading indicates the region consistent with the two constraints.

It can be seen from Figure 4 that in addition to the region of thermal plasma at a temperature of 5 10^6 K (consistent with the interpretation of Canizares et al [15]), there is a further region at a temperature of 4 10^5 K, but with 1% of high energy electrons. In the conditions expected in old SNR's involving low density shock-waves, the presence of such a fast electron component can be considered as a clear possibility. We therefore propose this second solution as a serious alternative to the previous interpretation.

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