Temp.# 11883
N84-20468

# THEORETICAL STUDIES OF X-RAY EMISSION FROM SUPERNOVA REMNANTS AND OTHER NON-EQUILIBRIUM ASTROPHYSICAL PLASMAS

Grant NAGW-117

Final Report

For the period 1 November 1980 through 29 February 1984

Principal Investigator

Dr. A. K. Dupree

March 1984

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
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| The Smithsonian Astrophysical Observatory is a member of the Harvard-Smithsonian Center for Astrophysics |

The NASA Technical Officer for this grant is Dr. Louis J. Kaluzienski, Code EZ-7, Headquarters, National Aeronautics and Space Administration, Washington, D.C. 20546.

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We have carried out a three year study of thermal X-ray emission from astrophysical plasmas. In order to improve the accuracy of both equilibrium and non-equilibrium thermal X-ray emission spectrum predictions, we have made new computations of electron excitation rates and dielectronic recombination rates, and we have extensively revised our computer codes to include recent results of other workers. Copies of the new version have been given to several groups experienced in using the older version, and the code will soon be made available to other groups analyzing X-ray or EUV data. The following sections describe the calculations we have made, the new rates we have incorporated into the codes, and applications of the updated codes to Supernova remnants and to O star winds.

**Pumping Iron: Atomic Processes in Fe XVII**

Fe XVII is the dominant ion of iron over a broad temperature range in coronal equilibrium due to its closed n=2 electron shell (neon isosequence) and the consequent low ionization and dielelectronic recombination rates. Its X-ray lines at 15 and 17 Å are the brightest X-ray lines observed in solar active regions. They are among the strongest features in the spectra of many late-type stars and of supernova remnants a few thousand years old, dominating the 1 keV iron complex for all but very high temperatures.

We have used the Distorted Wave collision strengths of J. Mann to compute the excitation rates to all 36 of the n=3 levels and have extended Mann's results to all of the n=4 levels for a total of 88 levels. The collision strengths were computed at 21 energies, so that the temperature dependence of the line emissivity can be reliably predicted. Radiative transition probabilities among all these levels were computed using the STRUCTURE code of R. Cowan, with configuration interaction and relativistic terms included. These were used to compute a full cascade matrix. As reported earlier by Loulergue and Nussbaumer (1975), cascades from higher levels dominate the excitation of the strong $2p^6 - 2p^5\,3s$ transitions at 17 Å.

A major improvement in our calculations is the inclusion of the contribution of resonances to the excitation rates. An approximate calculation based on the Quantum Defect Method was used to select the most important resonance series for more detailed computations. We used the STRUCTURE code to compute the autoionization rates of hundreds of doubly excited levels of Fe XVI to the ground level and 36 excited levels of Fe XVII. These yield resonance excitation rates which are probably accurate to 10 - 20%.

Resonances in excitation cross sections are closely related to the process of dielectronic recombination. Jacobs et al (1977) reported that autoionization to excited levels reduces the dielectronic recombination rate of Fe XVII by a factor of ten. We find that the Jacobs et al rates are reliable for low Z elements, but for Fe XVII, the reduction due to intermediate excited levels is only about 20%. The Jacobs et al dielectronic recombination rates being used in all current X-ray spectrum codes are erroneous for $Z > 10$, and we have developed approximate corrections based on our detailed Fe XVII calculations and more approximate Quantum Defect calculations for the lithium and other iso-sequences.

We find that the easily observable 3s / 3d line ratio is a promising temperature diagnostic for use in non-equilibrium plasmas such as supernova remnants. Figure 1 shows the predicted ratios of the three components of the 3s multiplet to the 15.01 Å resonance line as a function of temperature. Solar observations can provide a test of the predictions, though the scatter in the observed line ratios suggests substantial errors in the measurements. Our calculations give T ≈ 2 x $10^6$ K for solar active regions and ≈ 5 x $10^6$ K for a flare observed by SMM (R. Stern, private communication). The ratio of the $^3P_2$ and $^3P_1$ components of the $2p^6$ - $2p^5 3s$ multiplet predicted by our rates is in better agreement with SMM observations (Phillips et al 1982) than is the prediction of Loulergue and Nussbaumer (1975). The dielectronic recombination rates we have found seem to be corroborated by solar EUV observations (Doyle, Raymond and Noyes 1983), in that the strengths of lines of sodium-like ions were badly underestimated in the earlier models, but this analysis is not yet complete.

The Fe XVII calculations are presented in a paper submitted to Ap. J. (Smith et al 1983).

**Improved atomic data incorporated in codes.**

Ionization Rates: Younger (1982) Distorted Wave ionization cross sections. Cowan and Mann (1979) inner shell excitation followed by ionization rates found to be to be underestimates. Ionization from metastable levels of Be-, B-, and Mg-sequences (Vernazza and Raymond 1979) included.

Recombination: Dielectronic rates done in detail for Fe XVII and approximately for other ions. Photoionization cross sections form Reilman and Manson (1979) used with the principle of detailed balance to compute radiative recombination rates and spectra. Recombination to excited levels of He-like ions from Mewe and

Schrijver (1978).

Excitation: Extensive Distorted Wave collision strength calculations included; Pradhan and Shull (1981, He sequence), Hayes and Seaton (1978, H-sequence), and results of A.K. Bhatia, J. Mann , and H. Mason for other sequences. Resonances included for many intercombination transitions. Satellite lines treated separately for He-like ions. K$\alpha$ lines of Fe XVIII - XXIII from Merts et al (1976). For most applications, the improvements to the $2\ell$ - $3\ell'$ excitation rates are most important, particularly the Fe 1 keV complex.

**Applications.**

We have used the Distorted Wave ionization rates and reliable excitation rates to model the X-ray, ultraviolet and optical emission line intensities from non-radiative shock waves. The models were used to interpret observations of a filament at the edge of the Cygnus Loop. The shock velocity, the pre-shock ionization state, and the elemental abundances (unaffected by destruction of grains) were derived. Most important, the models provide moderately strong evidence that the electron and ion temperatures come into equilibrium on the Coulomb collision time scale, rather than the much shorter plasma turbulence time scale (cf. McKee and Hollenbach 1980). These results are presented in a recent paper in Ap J. (Raymond et al 1983).

Winds driven by radiation pressure in lines have long been known to be unstable (Lucy and Solomon 1970; MacGregor, Hartmann and Raymond 1979; Owocki and Rybicki 1983). While the non-linear behavior of this instability has not yet been treated in detail, it seems safe to assume that shocks form. If the shock velocity is high enough, these shocks might account for the X-ray emission of O stars (Lucy and White 1980). In collaboration with J. Krolik, we have computed the X-ray emission spectra of shock waves in the winds of O stars. The code also computes the line opacities in the shocked gas, and therefore the radiative driving force available to drive the shock. For example, the spectrum emitted by a 400 km/s shock in a gas whose density is $10^{11}$ $cm^{-3}$ is shown in Figure 2. Further models are being computed.

Another project dealt with the X-ray emission from the boundary layers of cataclysmic variables. A paper on the subject has been submitted (Patterson and Raymond 1984), and work is continuing. At present, we are concentrating on the models of the winds observed during dwarf nova outburst.

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Atomic Processes in Fe XVII, B.W. Smith, J.C. Raymond, R.D. Cowan and J. Mann, submitted to Ap. J.

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The Structure and Emission of a Non-Radiative Shock, J.C. Raymond, in "Supernova Remnants and Their X-ray Emission" (IAU Symposium 101), J. Danziger and P. Gorenstien, eds. (Dordrecht: Reidel).

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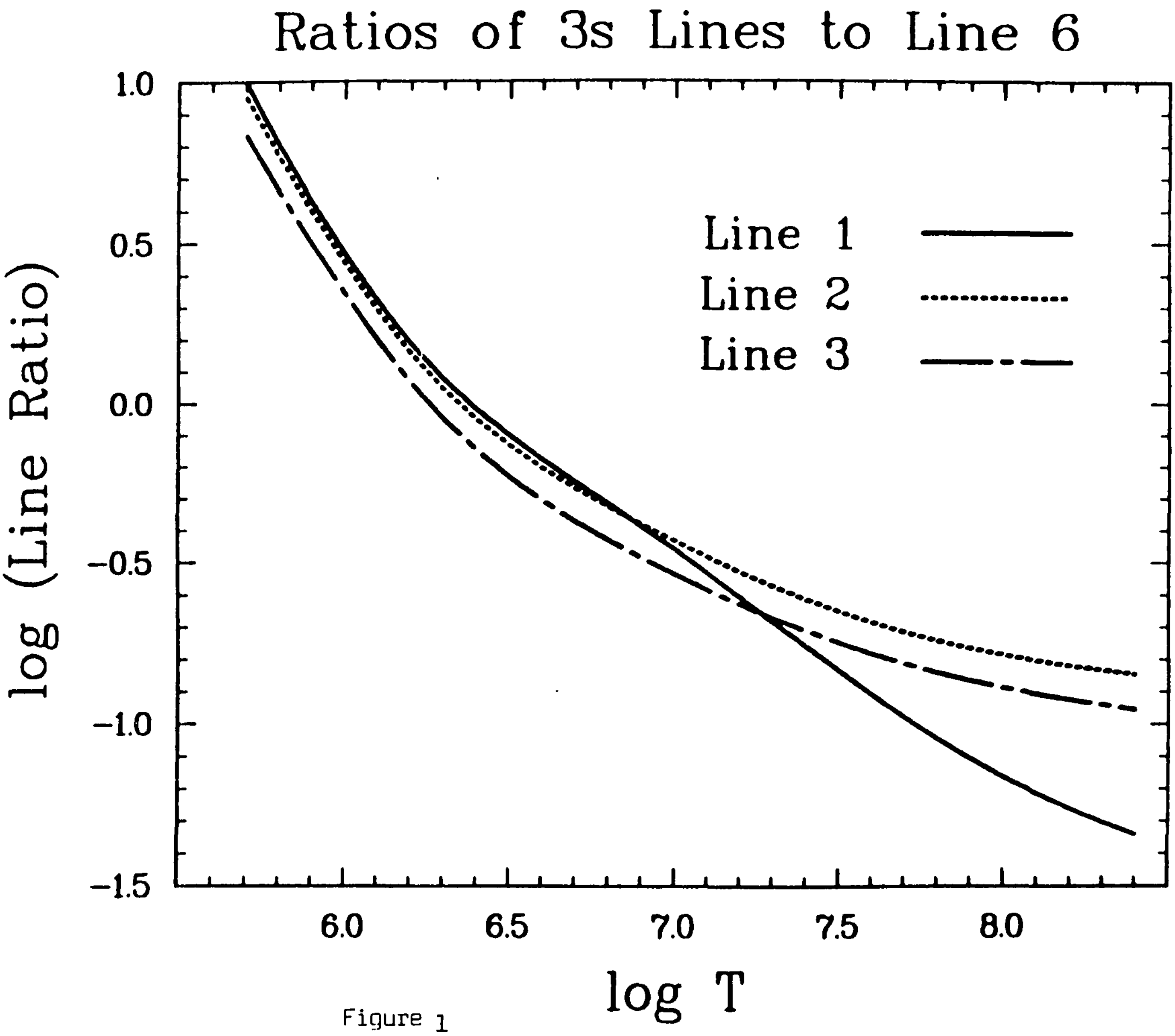
Ratios of 3s Lines to Line 6
1.0
0.5
0.0
−0.5
−1.0
−1.5
log (Line Ratio)
Line 1
Line 2
Line 3
6.0
6.5
7.0
7.5
8.0
log T

Figure 1