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Abstract

X-ray spectra from Alcator C-Mod plasmas have been collected using a high wavelength resolution, five spectrometer array during a wide range of operating conditions, providing a large variety of diagnostic information. Each independently scannable von Hámos type spectrometer has a wavelength range of 2.8 to 4.0 Å, and the complete Rydberg series of helium- and hydrogen-like argon have been observed. Spectra of Δ n = 1 ground state transitions and satellites taken along different chords have been simulated using the results from a collisional-radiative model and the MIST transport code. Line ratios are very sensitive to the electron temperature profile and good agreement is found with ECE profiles. Line intensities have been utilized to obtain absolute argon densities and argon recycling coefficients. The widths of the strongest lines have been used to deduce ion temperature profiles. Transitions from around n = 9 to the ground state are populated by charge-exchange in the outer regions of the plasma and these line intensities have been used to determine the neutral hydrogen density profile. Spectra from helium-like scandium have been obtained during injection experiments and time histories and line intensities have been utilized to determine impurity transport coefficients. Δ n = 2, 3 and 4 ground state transitions in molybdenum charge states around neon-like have been observed and used to measure the absolute molybdenum density.

Introduction

A five chord, independently scanable, high resolution x-ray spectrometer array[1] has been installed on the Alcator C-Mod tokamak[2]. Each von Hamos type spectrometer consists of a variable entrance slit, a quartz crystal (2d=6.687 Å) and a position sensitive proportional counter detector. Each spectrometer has a resolving power of 4000, 3 cm spatial resolution and a wavelength range of 2.8 to 4.0 Å. Spectra are typically collected every 50 ms during a discharge, with 120 mÅ covered at any one wavelength setting. Much of the diagnostic information comes from observations of the strongest lines of helium- and hydrogen-like argon, from argon seeding of the plasmas. Spectra of $\Delta n = 1$ ground state transitions and satellites taken along different chords have been simulated using the results of a collisional- radiative model[3] and the MIST[4] transport code. Certain line ratios are very sensitive to the electron temperature and can be used to determine the profile shape. Absolute line intensities can be used to determine impurity densities in the plasma, for example from intrinsic elements such as molybdenum. Intensities of injected impurities can provide information about impurity penetration and screening. Line widths have been used to measure ion temperature profiles under a wide range of operating conditions. High n transitions in argon, which are populated by charge exchange recombination, have been used to determine the neutral hydrogen density profile in the plasma. Time histories of scandium emission taken along different chords have been used to determine impurity transport coefficients following injection by laser blowoff.

Plasma Diagnosis

Over most of the plasma volume in typical Alcator C-Mod discharges, the upper level of the resonance line (w, 3.9492 Å, $1s2p\ ^1P_1$ - $1s^2\ ^1S_0$) in Ar^{16+} is populated by electron impact excitation of helium-like argon. The upper level of the satellite k (3.9903 Å, $1s2p^2\ ^2D_{3/2}$ - $1s^22p\ ^2P_{1/2}$) is populated by dielectronic recombination of helium-like argon. The intensity ratio k/w is independent of the electron and helium-like argon densities, and is only a function of the electron temperature. The measured ratios have been used to determine the electron temperature profile, an example of which is shown in Fig. 1. Plasma parameters for this 5T, hydrogen discharge were $I_P = .45$ MA, $T_{e0} = 1500$ eV (from ECE) and an average electron density of 8 x $10^{19}/m^3$. This profile is in good agreement with that determined from the ECE diagnostic[5], as shown by the solid curve. The dotted curve is a gaussian profile with a 1/e width of 12.8 cm. This technique is not valid in the outermost regions of the plasma where the resonance line is populated by radiative recombination.

The absolute sensitivities of the individual spectrometers have been calculated from geometric factors, crystal reflectivities, window transmissions and detector sensivities. A typical value of the spectrometer luminosity is 7 x 10^{-13} m^2 sr. From the measured spectra taken along different chords, absolute brightnesses can then be deduced. If the population mechanisms of the upper levels of the individual lines and the density profiles of the individual charge states are known, then absolute total impurity density profiles can be determined. In practice, the electron temperature and density profiles are taken from the ECE and TCI[6] diagnostics, respectively, and the charge state density profiles are calculated from the MIST code. Central argon densities measured during a sequence of discharges with identical argon puffing are shown in Fig. 2 as a function of central electron density. The argon density decreases with increasing electron density. Changes in the edge electron density and temperature as the central electron density is increased can account for this. Similar results have been obtained for scandium densities[7] after injection of scandium by laser blow-off. In contrast to the scandium case, where 10% of the injected scandium reaches the plasma center, only about 1% of the total number of injected argon atoms reaches the core. This is possibly due to a larger initial radial velocity of the injected neutral scandium compared to the edge recycling argon. Typical values for the central molybdenum density determined from 4d-2p transitions in Mo^{32+} from intrinsic molybdenum are in the $10^{16}/m^3$ range, and also exhibit a decreasing trend with increasing electron density.

The observed widths of the individual lines are due to contributions of instrumental widths and to doppler broadening from impurity motion. If the instrumental contribution is known, the ion temperature and profile can be measured. The instrumental widths were determined by comparing the observed widths of two lines with different masses and assumed equal ion temperature. In this case the 4d-2p transition of Mo^{32+} (100 AMU) at 3.7398 Å and the 2p-1s Lyman α doublet of Ar^{17+} (40 AMU) at 3.7311 and 3.7365 Å were used to determine the instrumental widths. Shown in Fig. 3 are two ion temperature profiles from four similar hydrogen discharges with I_p = .48 MA, T_{e0} = 1900 eV and a line averaged electron density of 8 x $10^{19}/m^3$. In this case the resonance line of Ar^{16+} was used for the doppler broadening measurements. The asterisks are for B_T = 5.3 T and the plus signs are for B_T = 3.5 T. The two curves are gaussian profiles with e^{-1} widths, a_T, of 13.3 and 15.8 cm, respectively. In the 5.3 T case, the profile is hotter and more narrow. This is certainly what is expected for the electron temperature profiles. If the current density profile is proportional to the electron temperature profile to the power 1.5, the central temperature should scale as $B_T{}^{.67}$. The ratio of the central ion temperatures in these two cases is 1.33, which is very close to $(5.3/3.5)^{.67}$= 1.32. If it is further assumed that the electron temperature profile shape is gaussian, the width a_T(cm) = $42.7(I_P/B_T)^{.5}$ (for Alcator C-Mod), where the central safety factor is assumed to be .9, I_P is in MA and B_T is in tesla. The calculated values of a_T for the profiles of Fig. 3 are 12.9 and 15.8 cm, using this model for the ion temperature profile width, close to the observed values. Shown in Fig. 4 is the ion temperature gaussian profile width as a function of plasma current for a sequence of 5.3 T discharges. Shown by the solid curve is the expression described above. The agreement is fairly good, except at the highest currents, where the profiles are broad and not well described by gaussians. This model is also only strictly valid for electrons, and the effects of elongation were not taken into account. Typical values for the elongation in Alcator C-Mod are around 1.5.

The entire Rydberg series, $1s^2$ - 1snp, in Ar^{16+} from n = 2 to n = 16 has been observed. The n = 9 transition at 3.0451 Å can be populated by charge exchange recombination if the neutral density is relatively large in a region of the plasma where sufficient Ar^{17+} is present. From the intensity of the line, the neutral density can be determined[8], given the measured electron temperature profile and the Ar^{17+} density profile from MIST. Information about the neutral hydrogen density profile has been obtained for a 5.3 T, .82 MA discharge with a central electron density of $1.2 \times 10^{20}/m^3$ and a central electron temperature of 1800 eV. In practice, a neutral density profile is assumed, and the contribution to the $1s^2$ - 1s9p line from charge exchange is calculated and compared to the observed spectra taken along different lines of sight. The assumed choice for the neutral density profile is generated from the FRANTIC[9] code where the only free parameter is the neutral density at the last closed flux surface. Spectra taken along chords through the bottom half of the torus are consistent with the neutral density profile shown by the solid dots in Fig. 5. The situation is very different in the top half of the machine; the neutral density profile shown by the open boxes in Fig. 5 was deduced from the spectrum taken along a line of sight which passes 18 cm above the midplane. There is a factor of at least 100 difference in the edge neutral density comparing the top and bottom of this particular discharge.

The time histories of individual lines at different radii of atoms injected by laser blowoff can provide information concerning impurity transport in the plasma. In particular, the resonance line of helium-like Sc^{19+} has been used to measure impurity transport coefficients, and typical values are in the vicinity of 5×10^3 cm^2/sec for the diffusion coefficient and close to 0 cm/sec for the convective velocity.

Conclusions

A five chord, high resolution x-ray spectrometer array has been used to provide a large amount of diagnostic information about Alcator C-Mod plasmas. In particular, from the spectra of injected argon, electron and ion temperature profiles, argon density profiles and neutral hydrogen density profiles have been determined. From observations of injected scandium, impurity transport coefficients have been measured and the effects of edge impurity screening have been characterized. Observations of intrisic molybdenum have been used to determine the molybdenum density in the plasma.

Acknowledgements

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Figure Captions

Fig. 1 The electron temperature profile determined from the ratio k/w.

Fig. 2 The central argon density as a function of central electron density.

Fig. 3 Ion temperature profiles for $B_T = 5.3$ and 3.5 T.

Fig. 4 The ion temperature profile gaussian width as a function of plasma current.

Fig. 5 The neutral density profiles calculated from the FRANTIC code deduced from measurements on the top half (solid circles) and the bottom half (open boxes) of the machine.

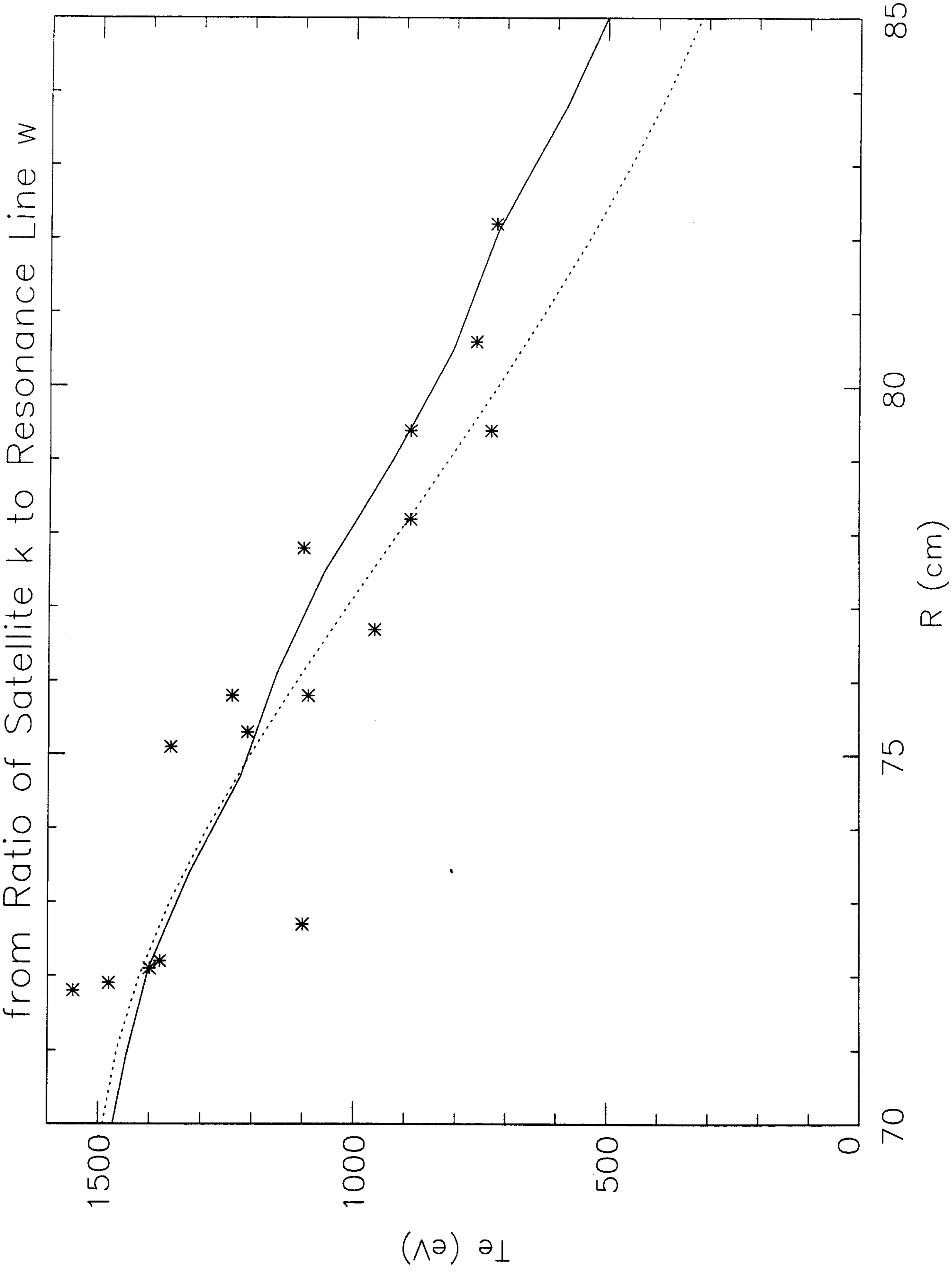
from Ratio of Satellite k to Resonance Line w
Te (eV)
0
500
1000
1500
R (cm)
70
75
80
85

Figure 1

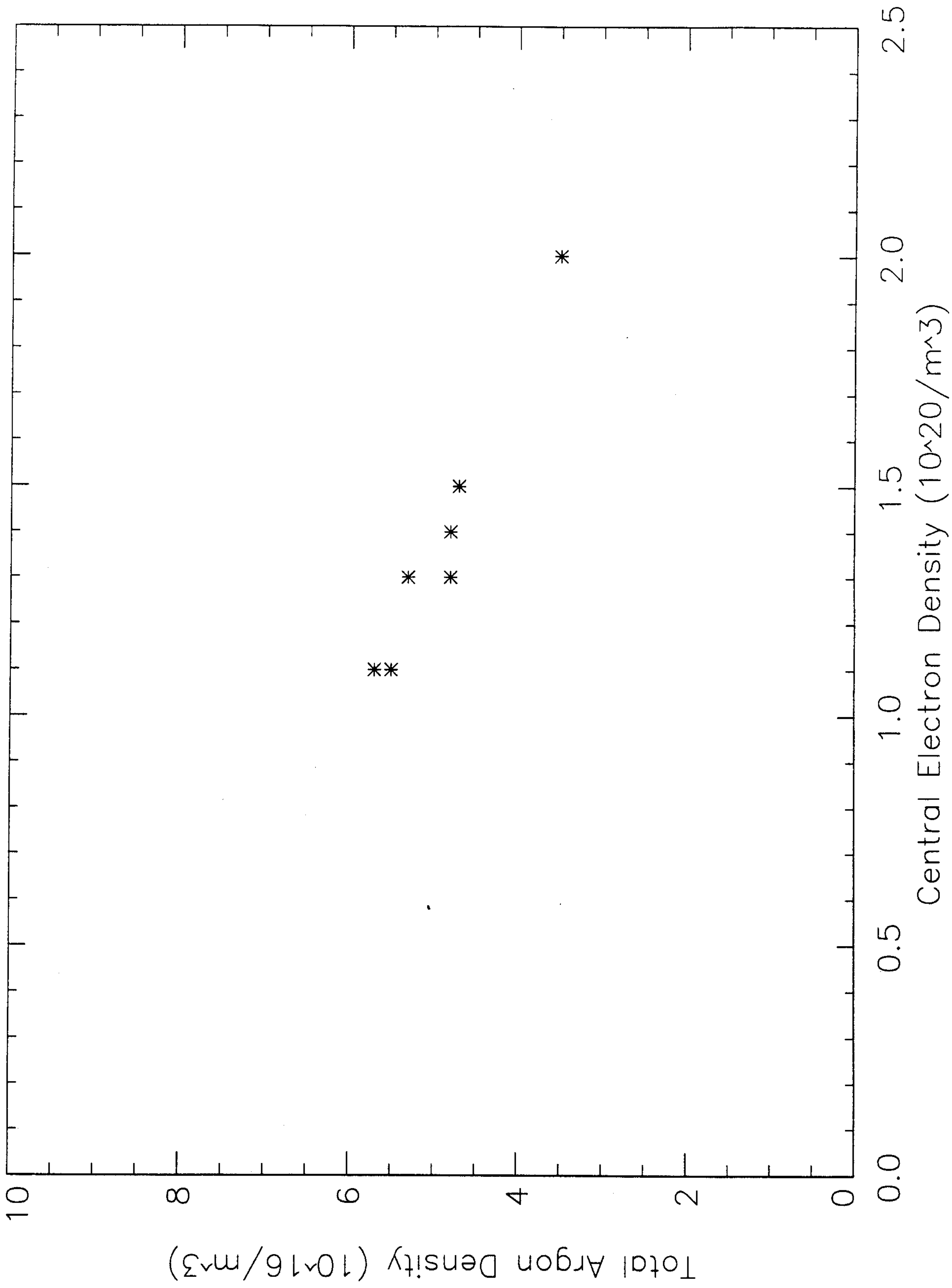
0.0
0.5
1.0
1.5
2.0
2.5
Central Electron Density (10^20/m^3)
0
2
4
6
8
10
Total Argon Density (10^16/m^3)

Figure 2

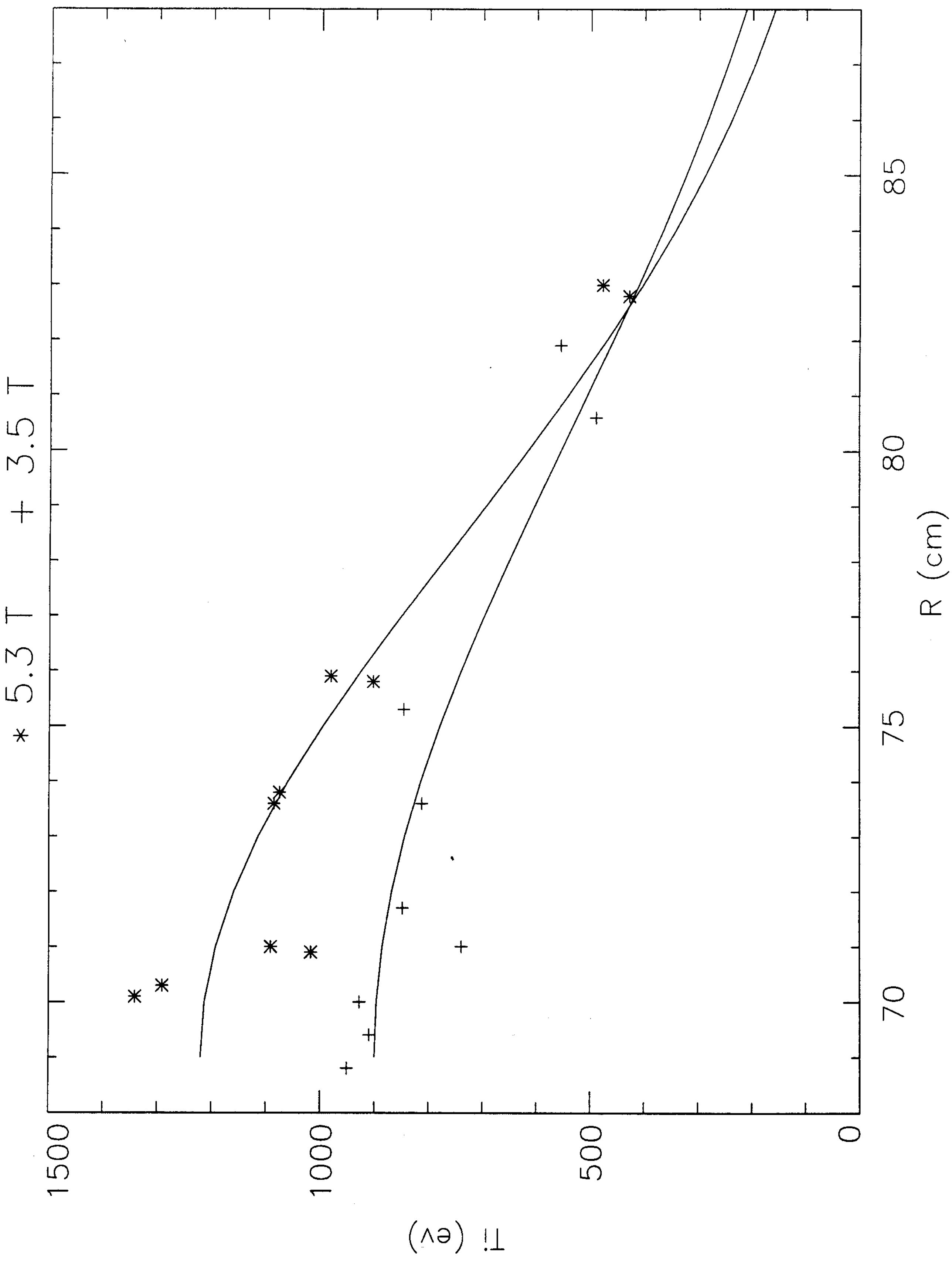

Figure 3

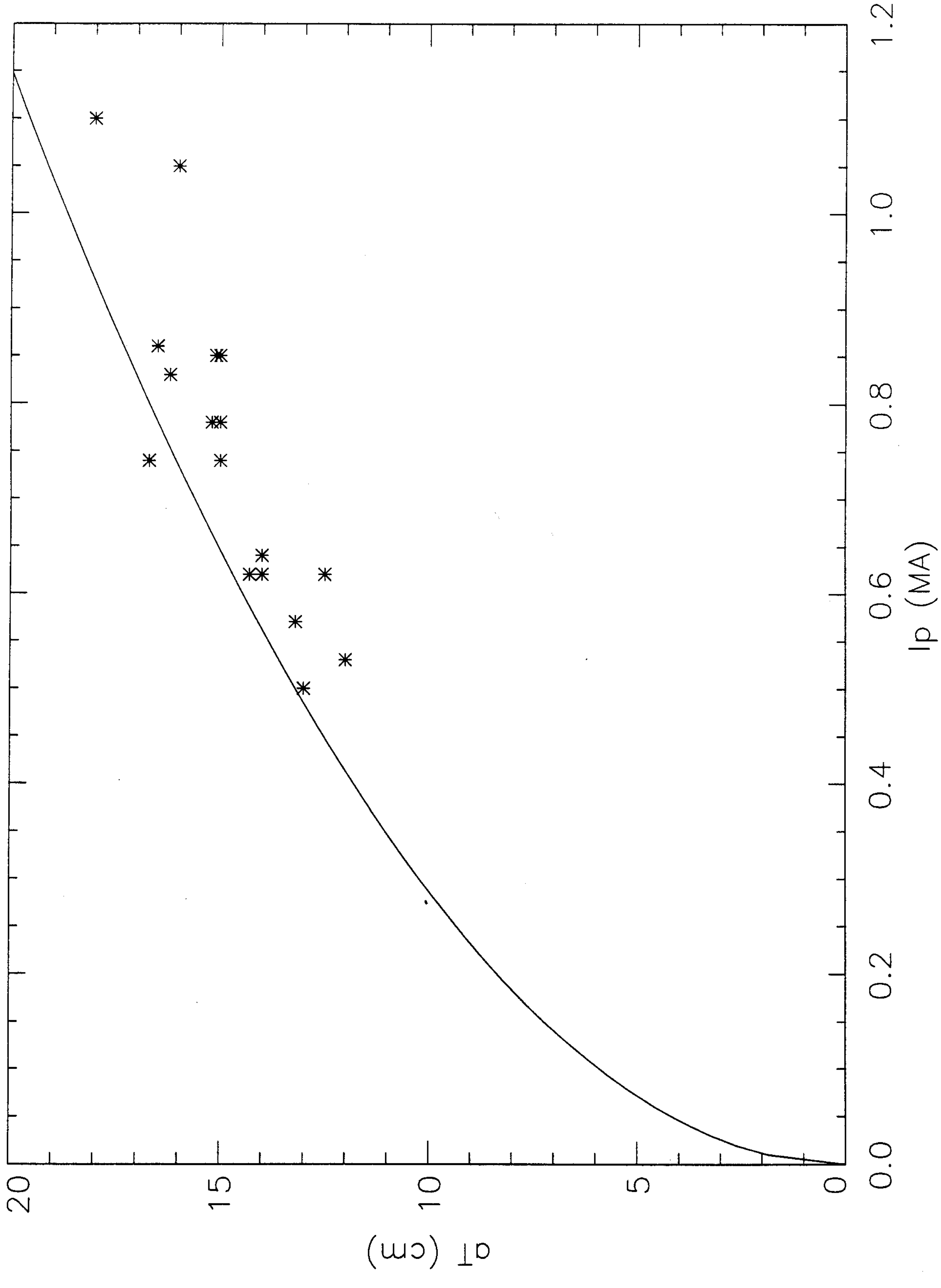

Figure 4

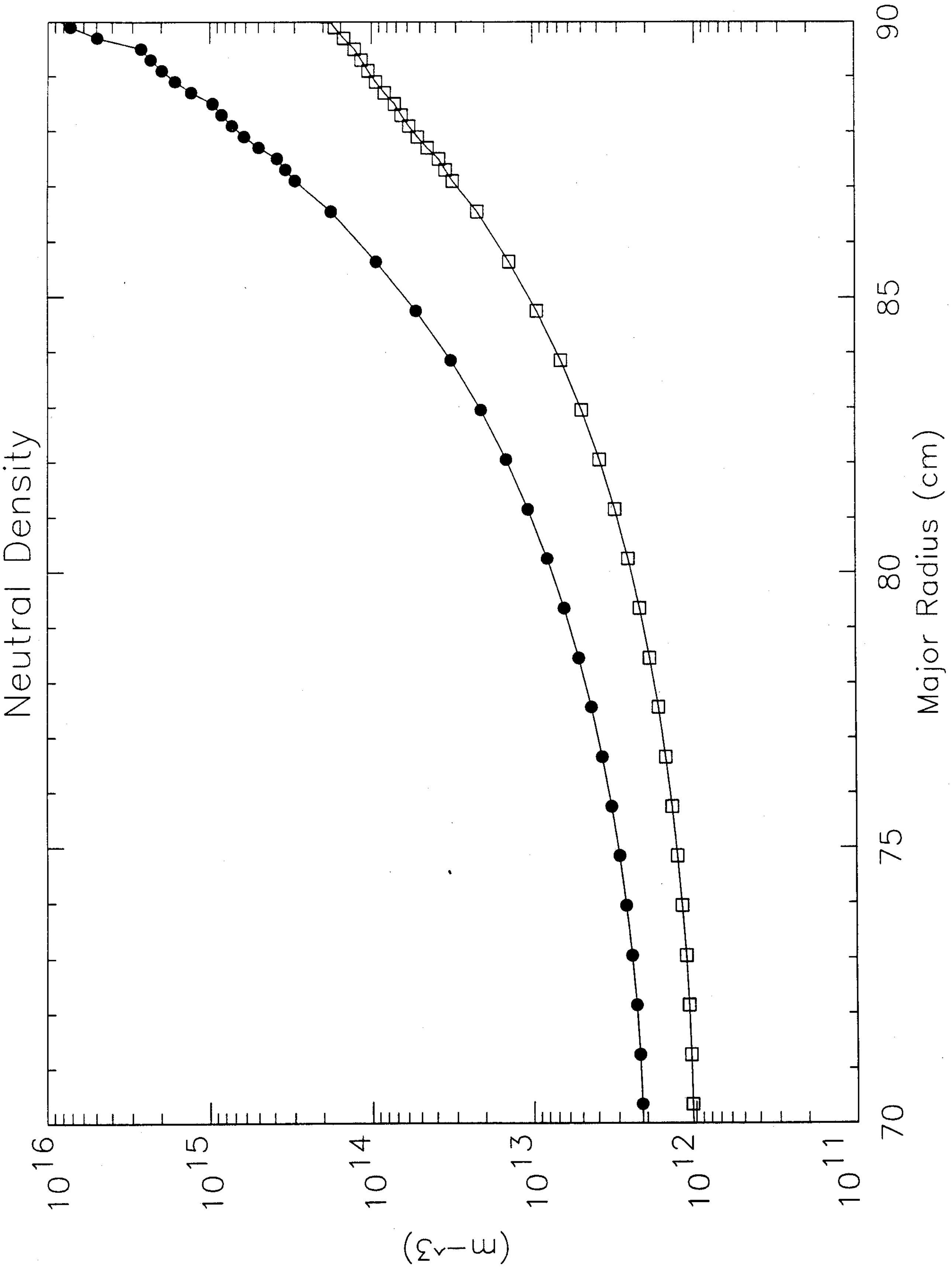
Neutral Density
Major Radius (cm)
70
75
80
85
90
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
(m^{-3})

Figure 5