9.2 Collisional Ionization: Astrophysical and Fusion Applications

J. M. Shull

Department of Astrophysics and JILA, University of Colorado and National Bureau of Standards and Laboratory for Atmospheric and Space Physics, Boulder, Colorado, U.S.A.

9.2.1 Introduction

For illustration of the effects of electron-impact collisional ionization, there are few less vivid examples than the hot astrophysical plasmas in stellar coronae, interstellar and intergalactic gas, and supernova remnants. However, laboratory studies in plasma physics have also provided a profitable interchange of data and theoretical calculations between the controlled fusion and astrophysics communities. In this review, I shall describe how basic data on collisional ionization have been used in both areas to obtain diagnostics of hot plasmas in states of equilibrium and disequilibrium.

9.2.2 Astrophysical Plasmas

Matter in the universe is predominantly hydrogen (H) and helium (He), with small amounts (approximately 1% by mass) of heavier elements such as C, N, O, Ne, Na, Mg, Si, S, Ar, Ca, and Fe. In many astrophysical environments, H and He are almost fully ionized as a result of radiative or collisional ionization. In such situations, the electrons are donated by H and He, and partially ionized heavy elements take on key roles as coolants of the plasma, diagnostics of physical conditions, and opacity sources to the transport of radiation.

Fig. 9.2-1 shows an optical photograph of the Crab Nebula, the remnant of a supernova explosion in 1054 A.D. These $10^{51}$ erg explosions, which terminate the lives of massive stars, heat and ionize vast portions of interstellar gas with their blast waves (McCray and Snow, 1979). Although the ionization state in the Crab Nebula is also strongly influenced by relativistic electrons and radiation from a rapidly spinning neutron star (pulsar) at the center, conditions in other young remnants are dominated by collisional ionization in hot $(10^7 - 10^8$ K) plasma with a Maxwellian distribution of electron velocities. Fig. 9.2-2 illustrates the $0.5 - 4.5$ keV X-ray line and continuum emission from one such remnant, observed by the Solid State Spectrometer (SSS) aboard NASA's HEAO-2 satellite. Similar X-ray line emission has been detected from the low-density ($n_e \approx 10^{-3}$ cm$^{-3}$) intergalactic gas in rich clusters of galaxies (Mushotzky et al., 1978; Jones et al., 1979), while ultraviolet lines characteristic of somewhat cooler gas have been seen in active stellar chromospheres (Fig. 9.2-3).
Fig. 9.2-1. Image enhancement of [O III] photograph of Crab Nebula (Gull and Fesen, 1982), showing faint jet at outer boundary and filaments resulting from 1054 A.D. supernova explosion.
Fig. 9.2-2. X-ray spectrum of Tycho's supernova remnant (1604 A.D.), taken by the solid state spectrometer aboard the HEAO-2 X-ray observatory (Szymkowiak et al., 1985). Positions of prominent He-like emission lines are indicated.

Fig. 9.2-3. Composite ultraviolet spectrum from *International Ultraviolet Explorer* satellite (Linsky, 1982) of chromospheric activity in the RS CVn-type star II Peg.

9.2.2.1 Coronal Equilibrium

Following the observation that the visible surface (photosphere) of the sun is surrounded by a hot ($2 \times 10^6$ K), extended corona of moderate density ($n_H \approx 10^{10} - 10^{12}$ cm$^{-3}$), astrophysicists developed the "coronal equilibrium" model.
(see e.g. Jordan, 1969, 1970) to describe the distribution of ionization states, the emission rate of electromagnetic radiation, and the transport properties of the plasma. With broad applicability to low-density plasmas in which collisional ionization dominates radiative ionization, this model is now used quite generally to describe the state of gas and emission in interstellar and intergalactic space, far from any "coronae".

In a low density plasma with electron density \( n_e (\text{cm}^{-3}) \), the rate of change of density in ion state \( i \) is standardly expressed as

\[
1/n_e d n_i/dt = n_{i-1} C_{i-1} - n_i [C_i + \alpha_{i-1}] + n_{i+1} \alpha_i,
\]

where \( C_i(T) \) and \( \alpha_i(T) \) are the rate coefficients (\( \text{cm}^3 \text{s}^{-1} \)) for collisional ionization from and radiative plus dielectronic recombination to state \( i \). The coefficient \( C_i \) includes both direct (valence shell) ionization as well as autoionization following inner-shell excitation. Inner shell ionization is particularly important for ions in isoelectronic sequences with 1 or 2 valence electrons outside a closed shell (Cowan and Mann, 1979) — for example, the Li, Be, Na, Mg, Ca, or K-isosequences. Its relative importance to direct ionization increases with atomic charge. For large-scale plasma modeling, it is often convenient to adopt semiempirical analytic fits to \( C_i(T) \) and \( \alpha_i(T) \) — see Lotz (1968), Burgess et al. (1977), Crandall (1981), Younger (1982), Shull and Van Steenberg (1982) and Chapter 2.

If collisional ionization couples only adjacent ion stages, the steady state solution to equation (9.2-1) is

\[
n_{i+1}/n_i = C_i(T)/\alpha_i(T),
\]

(9.2-2)

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Fig. 9.2-4. Fractional abundances in various ionization stages of Fe, assuming coronal ionization equilibrium (Shull and Van Steenberg, 1982)
and equilibrium curves for the fractional ionization distribution of a given element may be computed solely as a function of electron temperature $T$ (see Fig. 9.2-4). A primary result of such calculations is the temperature, $T_{\text{max}}$, at which a given ion reaches its maximum fractional abundance. Double ionization complicates this model, invalidating equation (9.2-2) and necessitating matrix inversion of the steady state rate equations (9.2-1).

Equilibrium spectral emission models of hot, optically-thin, low-density plasmas (Raymond and Smith, 1977; Shull, 1981) are now a familiar tool in X-ray astronomy for deriving the temperatures, densities, and element abundances in space. After computing the equilibrium ionization fractions (equation 9.2-1), these models generate the spectral emissivity (ergs cm$^{-3}$ s$^{-1}$ eV$^{-1}$) of the plasma in the X-ray continuum (bremsstrahlung, radiative recombination, and 2-photon emission from metastable states of H-like and He-like ions) and emission lines (dominated by collisionally-excited lines from heavy elements, with some contribution from radiative recombination cascade and satellite lines from dielectronic recombination). By fitting theoretical emissivity models to X-ray spectra, one may derive the plasma electron temperature, the “emission integral” ($n_e^2$ times the emitting volume $V$), and the heavy element abundances relative to H and He. This extraction is simplified in astrophysical plasmas because the continuum is dominated by electron free-free emission in the Coulomb fields of H and He ions, while the line emission is produced by the trace heavy elements. Thus, the thermal continuum shape yields $kT$, and the line-to-continuum ratios yield the abundances; $n_e^2 V$ follows from the total flux normalization, since the emitting processes all result from binary collisions.

Fig. 9.2-5. X-ray spectrum of supernova remnant Puppis A (Winkler et al., 1981), taken by focal plane crystal spectrometer aboard HEAO-2 observatory. Note the 3 He-like lines of Ne IX (marked F, I, R), as well as H-like lines of Ne X and O VIII.
Ratios of emission line intensities may also be used to derive \( n_e \) and \( T \) (e.g. Doschek, Feldman, and Cowan, 1981). Densities usually follow from the ratio of a forbidden to an allowed line (the forbidden line intensity is density sensitive, owing to collisional de-excitation), while temperatures are derived from lines with significantly different excitation energies (which sample the Boltzmann factor, \( \exp \left[ -E/kT \right] \)). An elegant set of density and temperature diagnostic lines (Gabriel and Jordan, 1969, 1973; Pradhan and Shull, 1981) are the resonance \((2^1P - 1^1S)\), forbidden \((2^3S - 1^1S)\), and intercombination \((2^3P - 1^1S)\) lines of He-like ions is seen in solar flares (Culhane et al., 1981) and supernova remnants (Winkler et al., 1981; Fig. 9.2-5). Helium-like ions are remarkably stable in high-temperature plasmas, owing to their high excitation and ionization energies. Contributions to these lines from dielectronic “satellites” and inner-shell ionization also provide diagnostics of whether the plasma is in a transient ionizing or recombining state.

The coronal model neglects several processes which occasionally become important. First, at high densities \((n_e > 10^{14} \text{ cm}^{-3})\), one must include 3-body recombination (the inverse process to electron impact ionization), as well as the suppression of dielectronic recombination by electron collisional excitation and proton-impact redistribution of high-\( n \) states (Burgess and Summers, 1969; Weisheit, 1975). Second, in partially ionized plasmas, ion charge exchange with \( \text{H}^0, \text{He}^0, \text{ and } \text{He}^+ \) introducing additional parameters to the model’s rate equations (equation 9.2-1), particularly for ions such as \( \text{O} \text{II} \) and \( \text{Si} \text{III} \) which exchange their charge to the ground state of the next lower ion stage (Butler, Heil, and Dalgarno, 1980; Balunas and Butler, 1980). Third, the effects of photoionization must often be included if the gas is situated near a source of ultraviolet and/or X-ray radiation; the relative importance of such radiation is measured by the ratio, \( F/n_e \), of ionizing photon flux to electron density (Kallman and McCray, 1982). Finally, and most importantly, the assumption of ionization equilibrium is often violated in transient situations (an ionizing or recombining plasma).

### 9.2.2.2 Non-Equilibrium Effects

If the characteristic timescale \( t \) (e.g. age, transport time, or heating time) of a plasma is shorter than the ionization time, \( \tau_i = (n_e \, \zeta_i)^{-1} \), or the recombination time, \( \tau_r = (n_e \, \zeta_r)^{-1} \), then the plasma will be out of ionization equilibrium. As a result, a given element may be “underionized” (lower ionization stages than predicted by equilibrium; \( t < \tau_i \)) or “overionized” (higher ionization stages than equilibrium; \( t < \tau_r \)), with significant effects on the plasma emissivity and radiative cooling rate. In general, an underionized plasma radiates far more effectively, owing to the enhancement of ion stages with more bound electrons. Departures from equilibrium may also be gauged by the He-like line ratios described above.

Non-equilibrium ionization effects are of major importance, for example, in many young supernova remnants (Itoh, 1977; Shull, 1982), solar flares (Acton and Brown, 1978; Mewe and Schrijver, 1980; Gabriel et al., 1981) and interstellar shock waves (McKee and Hollenbach, 1980). Models of non-equilibrium plasmas are far more complicated, because they require the specification of the past ionization history of every parcel of emitting gas. While this ionization history has little effect on the free-
free X-ray continuum, the emission line strengths are quite sensitive to the dominant ion stage at a given temperature, as noted above. In \(10^5 - 10^6\) K gas behind 50 – 150 km s\(^{-1}\) interstellar shock waves, rapid collisional ionization has major effects on ultraviolet emission line intensities (Raymond, 1979; Shull and McKee, 1979).

9.2.3 Fusion Plasmas

Many of the same plasma diagnostics are used in fusion research, although the trace impurities sputtered off the wall (Cr, Fe, Ni, Mo, W) are often heavier elements than those occurring in space (TFR Group, Dubau and Loulergue, 1981 for Cr; Bitter et al., 1979 for Fe). However, low-mass elements (Si, S, Cl) are sometimes injected into Tokamak plasmas as spectroscopic probes of density, temperature, and transport rates. These diagnostics provide checks on the plasma confinement and fusion yield, while impurity transport rates may affect overall plasma properties such as radiative losses and plasma instabilities. Merts, Cowan, and Magee (1976) calculated the ionization equilibrium and power output (0.8 – 10 keV) from a thin (1%) Fe-seeded plasma with \(n_e = 10^{14}\) cm\(^{-3}\). Using the collisional ionization rates of Lotz (1967, 1968), they computed diagnostic spectra for X-ray \(K\alpha\) (1s – 2p) transitions near 6.5 keV. Källne, Källne, and

![Graph showing CL and Alcator C-0305.14 spectra](image)

Fig. 9.2-6. Example of measured He-like spectra of Cl (Källne, Källne, and Pradhan, 1983), showing line ratios x/y larger than average. These deviations could result from impurity transport or from ionization disequilibrium.
Pradhan (1983) have obtained spectra of He-like S and Cl in the Alcator C Tokamak (Fig. 9.2-6), analyzing the relative line ratios of resonance, forbidden, and intercombination lines for plasma conditions $kT = 1.0 - 1.8$ keV and $n_e = 1 - 7 \times 10^{14}$ cm$^{-3}$. Because the He-like manifold includes contributions from dielectronic recombination from H-like ions and inner-shell excitation/autoionization from Li-like ions, these theoretical models rely on calculations of the relative fractional ionization (in coronal equilibrium or disequilibrium). The Alcator plasma is sustained for several hundred milliseconds, but approaches equilibrium on a shorter timescale because of the high densities. However, other Tokamak devices operate at lower densities, and impurity transport may introduce nonequilibrium effects.

More recently, Petrasco et al. (1982) have demonstrated a powerful diagnostic technique with spatially and temporally resolved measurements of fully stripped, H-like, and He-like Si in the Alcator C Tokamak. The fully stripped ions are detected via the X-ray continuum from ground state radiative recombination and bremsstrahlung, and the H-like and He-like ions are measured from their $n = 2 - 1$ X-ray emission lines. By assuming that the total Si density is dominated by these 3 ion stages in coronal equilibrium, they solve for all 3 densities. The calibrations are most accurate for the fully stripped Si, since the collisional ionization rate of H-like Si has been calculated to 10% (Younger, 1980) and hydrogenic radiative recombination is well understood. The central ion densities in the Tokamak were found to be close to coronal equilibrium values, but the densities of fully ionized and He-like Si exhibited large fluctuations during internal plasma disruptions. Small deviations from equilibrium can be important, since they often result in enhanced radiative losses (Bitter et al., 1981), creating difficulties in achieving "break-even" controlled fusion.

References
