Progress in modeling astrophysical plasmas

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SRON

Astrophysical plasmas

- Cosmic X-ray sources broad range properties:
  - Sizes from ~10 km to 10^{24} m
  - Densities from 100 m^{3} up to solid state & beyond
  - Different environments & ionisation conditions: collisional ionised, photo-ionised, transient (recombining or ionising)
  - Emission & absorption (including charge transfer emission & dust absorption)
- Make tool to model these different sources with same, consistent set of atomic parameters

Spectroscopic codes at SRON

- Short history:
  - 1972 Mewe
  - 1975 Mewe-Gronenschild
  - 1985 Mewe-Gronenschild-van den Oord
  - 1990 Meka
  - 1994 Mekal
  - 1992 SPEX
- Evolution from plasma model to full astrophysical model including data analysis (fitting), plotting & diagnostic output

Requirements for updates

- Code must allow options for fast calculation yet accurate enough
- Minimise number of mathematical operations & data storage for the cross sections/rates
- Follow original strategy of Mewe: simple, accurate & fast approximations, but more accurate & complete than before
- Restrict to Z ≤ 30 (astrophysically most relevant)

Need for updates

- Example: Mewe code (still core in present SPEX models) approximates radiative recombination contribution by local power-law
- Okay for CIE but:
- Large deviations for recombining or ionising plasma

Radiative recombination

- Need individual rates to different excited shells for calculation of line spectrum
- Also need cooling rate associated to the recombination (kinetic energy captured electron averaged over the recombination rate)
- Start with hydrogen-like systems
Collisional ionisation
(with Ignone Urdampilleta)

Collisional ionisation for atoms and ions of H to Zn

Direct ionisation cross section fitting procedure:

\[ \sigma(Q) = a(Q) + b(Q)E + c(Q)E^2 + d(Q)E^3 \]

where:

- \( a(Q) \) = absolute cross section
- \( b(Q) \) = ionisation potential
- \( c(Q) \) = fine structure constant
- \( d(Q) \) = relativistic correction

Relativistic correction (Quarles 1976 and Tinschert et al. 1989):

\[ E = \left( \frac{1}{\sqrt{1 - v^2}} - 1 \right)^{-1} \]

Excitation Autoionization fit (Mewe 1972):

\[ \sigma(Q) = A + b/Q + c/Q^2 + 2d/Q^3 + \text{t} \text{flu} \]

Total ionisation cross section

\[ Q^2 (10^{-24} \text{m}^2/\text{keV}) \]

Total ionisation cross section

\[ Q^2 (10^{-24} \text{m}^2/\text{keV}) \]
Charge transfer modeling
(with Liyi Gu)

Simple Charge Exchange Model for
Astrophysical Plasmas

- Assume negligible electron collisional excitation in CX region
- Assume independent thermal/ionization equilibrium in cold/hot phases
- Most CX-populated n/l-shells obtained by fitting available data from atomic calculation

Simple Charge Exchange Model for
Astrophysical Plasmas

- Ionized heavy particles
- Neutral hydrogen (helium...)
- Interacting at interface, where heat exchange timescale > charge exchange timescale

CX dominates the recombination over other processes by \(10 \sim 10000\) in broad energy ranges.

He-like triplets and absorption
(with Missagh Mehdipour)

He-like R-ratio in Active Galactic Nuclei
(Seyfert 2 galaxies)

1s\(^2\)2s \(\rightarrow\) 1s\(^2\)2p\(^2\) \(\sim\) 1s\(^2\)2s \(\rightarrow\) 1s\(^2\)2p\(^{2}\) \(\sim\)

Fe XXIV absorption

OVII emission & OVI absorption

Fe XXV absorption & Fe XXIV absorption
Photoionised plasmas

- Irradiated plasma
- Two balance equations:

**Photons:**
- Photo-ionisation
- Heating by photo-electrons

**Electrons:**
- Radiative recombination (electron capture)
- Cooling by collisional excitation (followed by line radiation)

Photoionisation modelling

- Radiation impacts a volume (layer) of gas
- Different interactions of photons with atoms cause ionisation, recombination, heating & cooling
- In equilibrium, ionisation state of the plasma determined by:
  - spectral energy distribution incoming radiation
  - chemical abundances
  - ionisation parameter $\xi = L/nr^2$ with $L$ ionising luminosity, $n$ density and $r$ distance from ionising source; $\xi$ essentially ratio photon density / gas density
First balance equation: ionisation stages (1)

- *Same rates as for CIE plasmas:*
- Collisional ionisation
- Excitation auto-ionisation
- Radiative recombination
- Dielectronic recombination
- At low T, charge transfer ionisation & recombination

Second balance equation: energy

- Balance: heating = cooling
- Take care how heating etc is defined: we use here heating/cooling of the free electrons
- For instance, for \( e^+ + \text{ion} \rightarrow e^+ + \text{ion}^* + e^- \) we assign the *ionisation energy* \( I \) to the cooling of the free electrons

Performance (151 grid points)

- Same run on NGC 5548 obscured SED:
- XSTAR: 40 hours (& crashed for \( kT > 10 \) keV)
- Cloudy: 4 hours
- SPEX: 5 minutes
- Okay the above may depend on optimisation flags etc etc, but ....

Differences photoionisation models

(NGC 5548 obscured case)

Heating & cooling (NGC 5548 in 2013)

- *New for PIE plasmas:*
- Photoionisation
- Compton ionisation (Compton scattering of photons on bound electrons; for sufficient large energy transfer this leads to ionisation)

Performance

- Often people make a grid of models as function of few parameters \( \rightarrow \) table grid \( \rightarrow \) feed into favorite fitting program
- SPEX pion model allows fast instantaneous calculation & simultaneous fitting of the continuum of any shape; multiple stacked layers

The case of NGC 5548
Obscuration in NGC 5548

X-ray narrow line region

The SPEX project

SPEX web site

www.sron.nl/spex