# THERMAL X-RAY EMISSION FROM FORMING STARS

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18, MAY '09

- soft X-RAY emission from
- optically thin
- thermal plasmas (relatively hot)

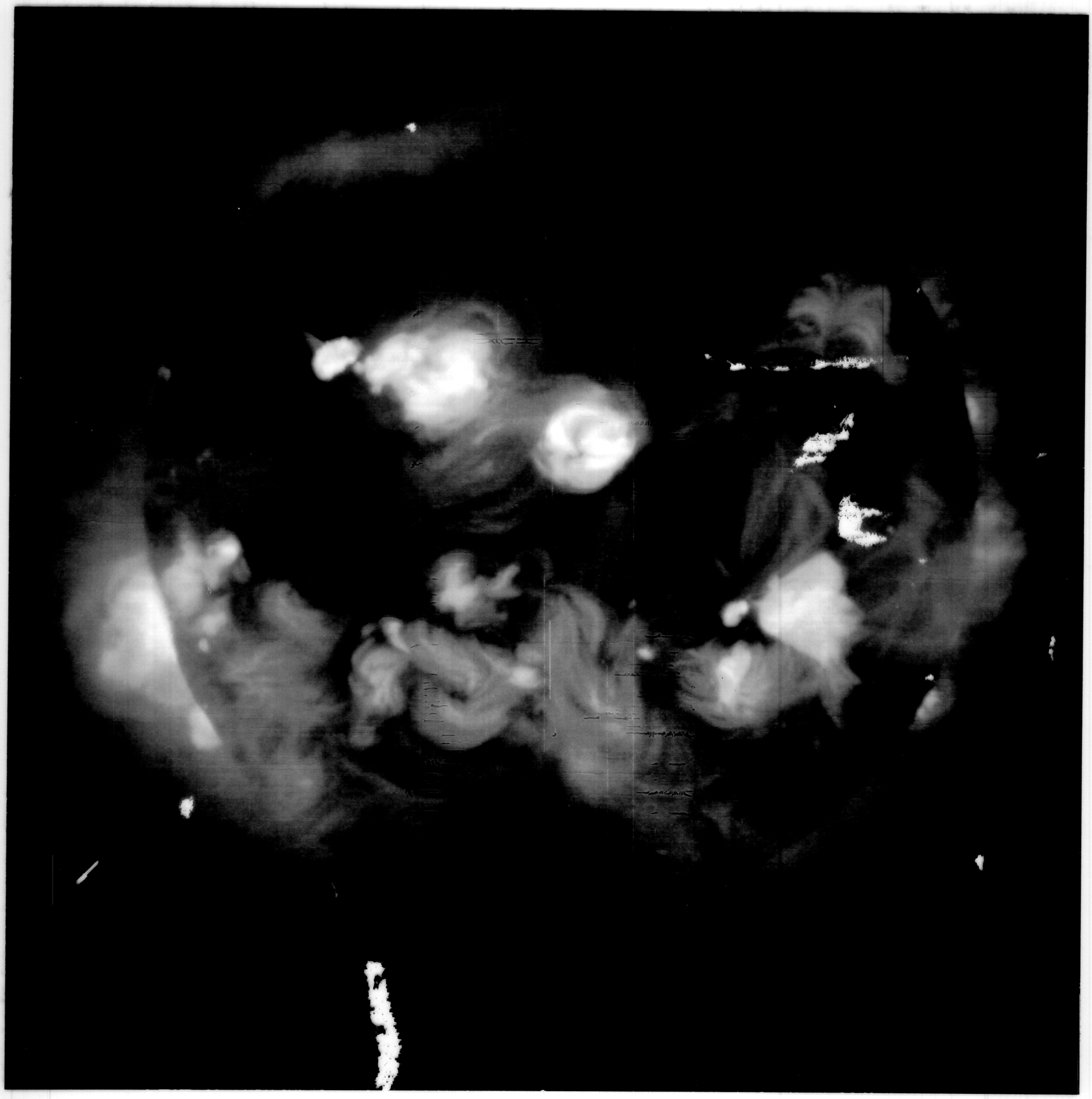
MANY EXAMPLES OF THIS KIND OF EMISSION:

- STELLAR CORONAE
- SNR
- HOT HALOS OF GALAXIES CLUSTERS

HERE WE FOCUS ON

EMISSION FROM FORMING STARS

CORONAE + SHOCKS (accretion, Jets...)



X-RAY IMAGE OF THE SOLAR CORONA

TAKEN W/ YOHKOH/XRT

- A USEFUL EXAMPEE OF A CORONA

- NOT VERY LUMINOUS

  $L_x \sim 10^{27}$ ergs/s     $10^{28}$ during flares!

- STELLAR CORONAE

  $L_x$ up to $10^{30}$!

- STILL . . .

  TELLS YOU OF STRUCTURES

  ETC

IN PRACTICE A LAB IN THE BACK YARD

# OPTICALLY THIN AND <u>CORONAL APPROX.</u>

$\lambda_{ph} >> D_{corona}$

photons escape freely
one sees the <u>whole</u> plasma

$\tau_{EUV;X} << 1$

## CORONAL APPROX

- LOW DENSITY $n_e < 10^{12}\ cm^{-3}$
- LOW PHOTON FLUX (ANYHOW THIN PLASMA)
- MAXWELLIAN ELECTRON ENERGY DISTRIB.
- EQUILIBRIUM $\frac{\partial n_e}{\partial t} = n_e \left( \omega_{i-1} n_i + \alpha_{i+1} n_{i+1} - (\omega_i + \alpha_i) n_i \right) = 0$
- MOST OF THE ATOMIC SYSTEMS AT <u>GROUND</u> STATE
- HOT $T > 10^5\ K$

<u>NOT</u> IN THERMAL EQUILIBRIUM

<u>NOT</u> IN LOCAL " " (LTE)

DETAILED EQUILIBRIUM

(i.e. each phoenomenon balanced by its opposite)

DOES NOT APPLY

AND SOME PHOENOMENA ARE BALANCED BY VERY DIFFERENT PHOENOMENA

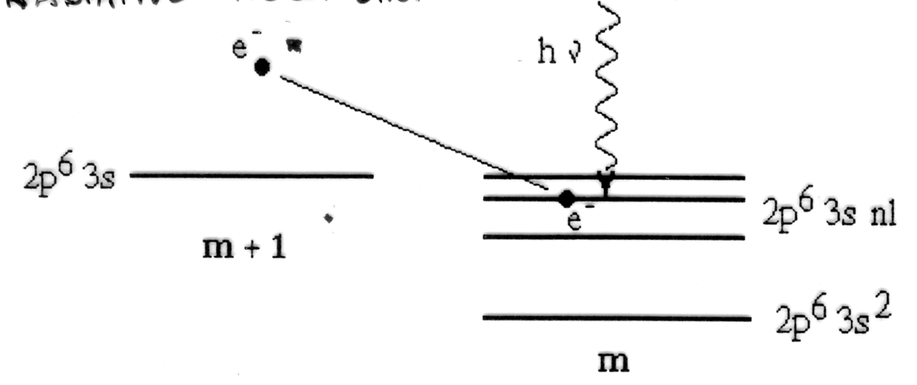
LET'S SEE AN IMPORTANT EXAMPLE

IONIZATION

# IONIZATION AND RECOMBINATION IN OPT. THIN PLASMAS

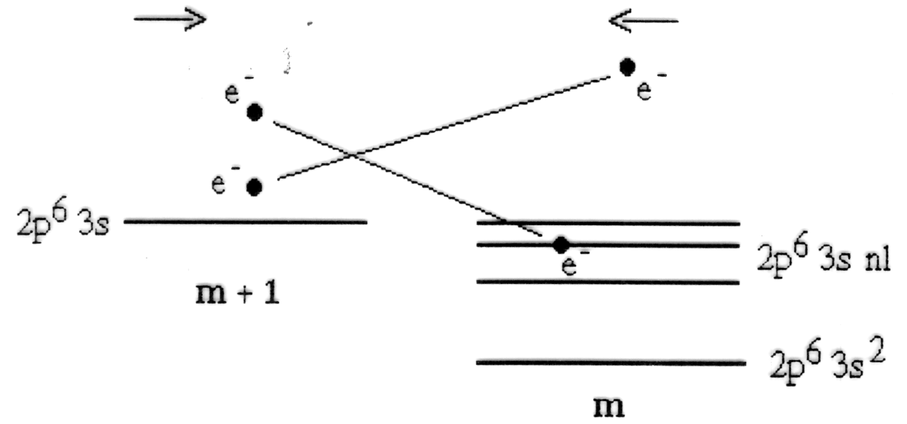
$$R_{rad\,rec}\, n_e \cdot N(x^{+m+1}) = n_{ph} N(x^{m+}) R_{rad\,ioniz}$$

RADIATIVE RECOMBIN. — RADIATIVE IONIZATION



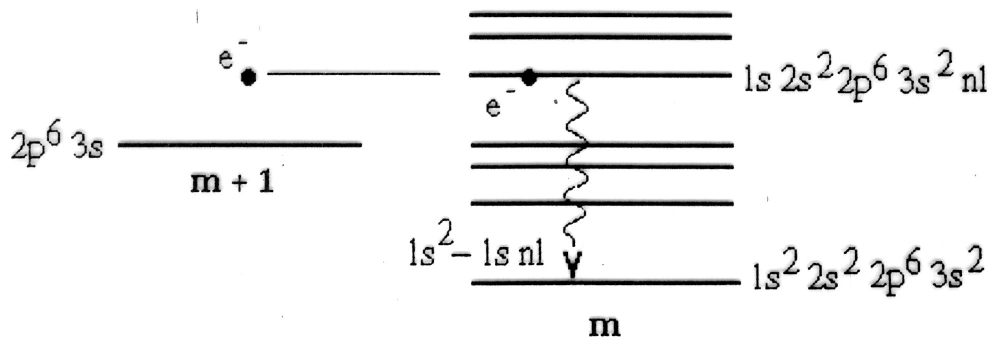

$$R_{3B\,rec.}\, n_e^2 N(x^{m+1}) = n_e N(x^{+m}) R_{coll.\,ioni}$$

**3 BODY RECOMB.** — COLLISIONAL IONIZATION




$$R_{die.\,rec.}\, n_e \cdot N(x^{m+1}) = R_{self\,ioniz.} N(x^{+m})$$

DIELECTRON RECOMB. — SELF-IONIZATION




(FROM LANDINI)

few photons! This side cannot work

$$R_{\text{rad. rec.}}\; n_e N(x^{m+1}) = n_{ph}\, N(x^m)\cdot R_{\text{rad ioniz}}$$

low density! This goes like $n^3$ less effective than $n^2$

$$R_{\text{3Body rec}}\; \overbrace{n_e^2 N(x^{m+1})} = \overbrace{n_e N(x^m)}^{\sim n^2}\; R_{\text{coll ioniz}}$$

SO ...

NATURE ACHIEVES A DIFFERENT BALANCE...

$$R_{\text{rad rec.}}\; n_e N(x^{m+1}) = n_e N(x^m)\; R_{\text{coll ioniz}}$$

radiative recombinations are balanced by collisional ionization

$$R_{\text{rad rec}}\cdot n_e N(x^{m+1}) = n_e N(x^m)\; R_{\text{coll. ioni}}$$

$$\frac{R_{\text{coll ioniz.}}}{R_{\text{rad rec.}}} = \frac{N(x^{m+1})}{N(x^m)} = f(T)$$

# CONFRONTO FRA DIVERSI CALCOLI DELL'EQUILIBRIO DI IONIZZAZIONE

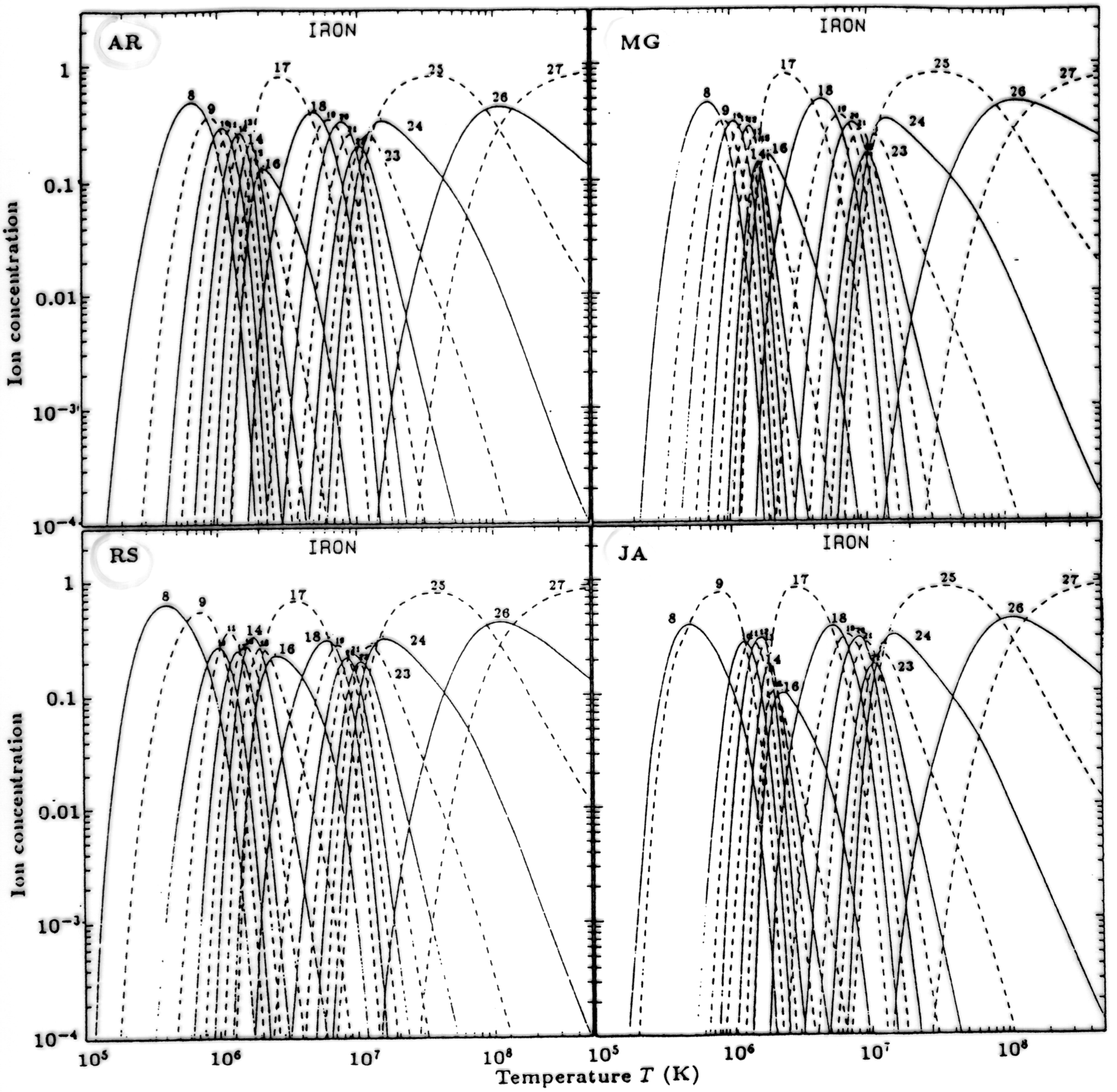


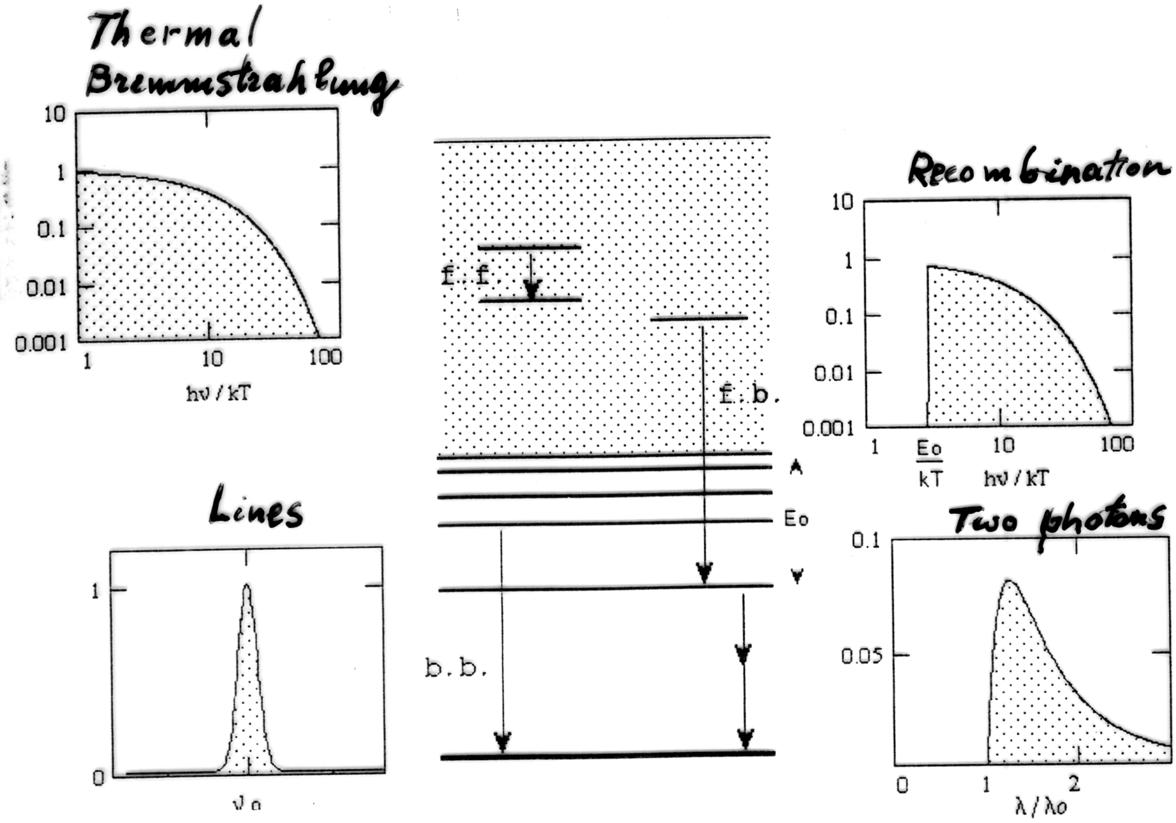

Figure 3a. Ion fractions as a function of temperature for iron as calculated by AR, RS, MG, and JA (see text). Ion stages are designated by numbers, e.g. 8 indicates ion $Z^{+7}$ (Fe VIII), etc.

AR = Arnaud & Rothenflug (1985)

MG = Mewe & Gronenschild (1981)

RS = Raymond & Smith (1977)

JA = Jacobs (1977)




Line emission

$$P(\mathrm{ph\,cm^{-3}\,s^{-1}}) = N_i A_{ij}$$

$$N_i = \frac{N_i}{N(X^{+m})} \; \frac{N(X^{+m})}{N(X)} \; \frac{N(X)}{N(H)} \; \frac{N(H)}{n_e} \; n_e$$

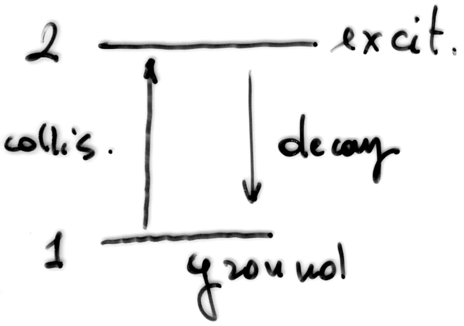
levels population — ionization equil. — Abundance — Hydrogen dens. / electron density

# LEVELS POPULATION

$j$-th level:

$$\overbrace{\underbrace{\sum_i n_j n_e C_{ji}}_{\text{collisions}} + \underbrace{\sum_{i<j} n_j A_{ji}}_{\text{decay}}}^{\text{OUT}} = \overbrace{\underbrace{\sum_{i>j} n_i A_{ij}}_{\text{decay}} + \underbrace{\sum_i n_i n_e C_{ij}}_{\text{collisions}}}^{\text{IN}}$$

In practice, only ground level is significantly populated (coronal condition)




$$n_e n_1 C_{12} = n_2 A_{21}$$

The population of level 2 is driven by collisional excitations from level 1

$$\phi = n_2 A_{21} E_2 = \underline{n_e n_1 C_{12} E_2} \propto \boxed{n_e^2}$$

True for resonance lines and the vast majority of lines (dominating the spectrum)

# EMISSION LINES INTENSITY

Resonance lines

$$N_i = \frac{N_e N_1 C_{1i}}{\sum_{j>i} A_{ij}}$$

Branching ≡ B ratio

$$I_{i1} = E_i N_i A_{i1} = \frac{N_e N_1 C_{1i}}{A_{i1}} \frac{A_{i1}}{\sum_{j<i} A_{ij}} A_{i1} =$$

$$= E_i N_e N_1 B C_1$$

Intensity directly proportional to collisional excitation and square of density

Collision rate depends on temperature

$$C(T_e) = 8.62\times10^{-6} \frac{\bar{\Omega}(E_0)}{\omega} T^{-1/2} e^{-E_0/kT} \quad \mathrm{cm^3\,s^{-1}}$$

$\bar{\Omega}$ ≡ collision strength

$E_0$ ≡ threshold energy

$\omega$ ≡ statistical weight of initial level

# THERMAL BREMSSTRAHLUNG

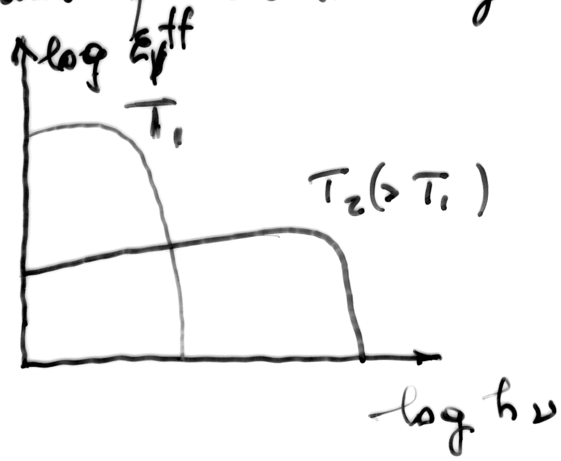
Spectrum $\epsilon_\nu^{ff} \propto T^{-1/2} e^{-h\nu/kT}$

since it is driven by collisional effects of plasma particles; $e^-$ against ions $\propto n_e N_i \propto n_e \frac{N_i}{n_e} n_e$
$\propto n_e^2 f(T)$


$N = \sigma v t \cdot n$
per each particle

per unit volume $n N = \underline{n} \cdot \sigma v t \underline{n} \propto n^2$
(the same for collisionally excited lines)

Spectrum




Emitted power per unit volume $\epsilon^{ff} \propto n^2 T^{1/2}$

Luminosity $L_X \sim 2.4 \times 10^{-27} \int T^{1/2} \underbrace{n_e^2 \, dV}_{\text{Emission measure}}$

# SPECTRAL SYNTHESIS

- CONSIDER MANY ELEMENTS, THEIR IONS, THE THOUSANDS OF LINES EMITTED

- CONSIDER OTHER EMISSION MECHANISMS

- TAKE INTO ACCOUNT HOW THEY DEPEND ON T

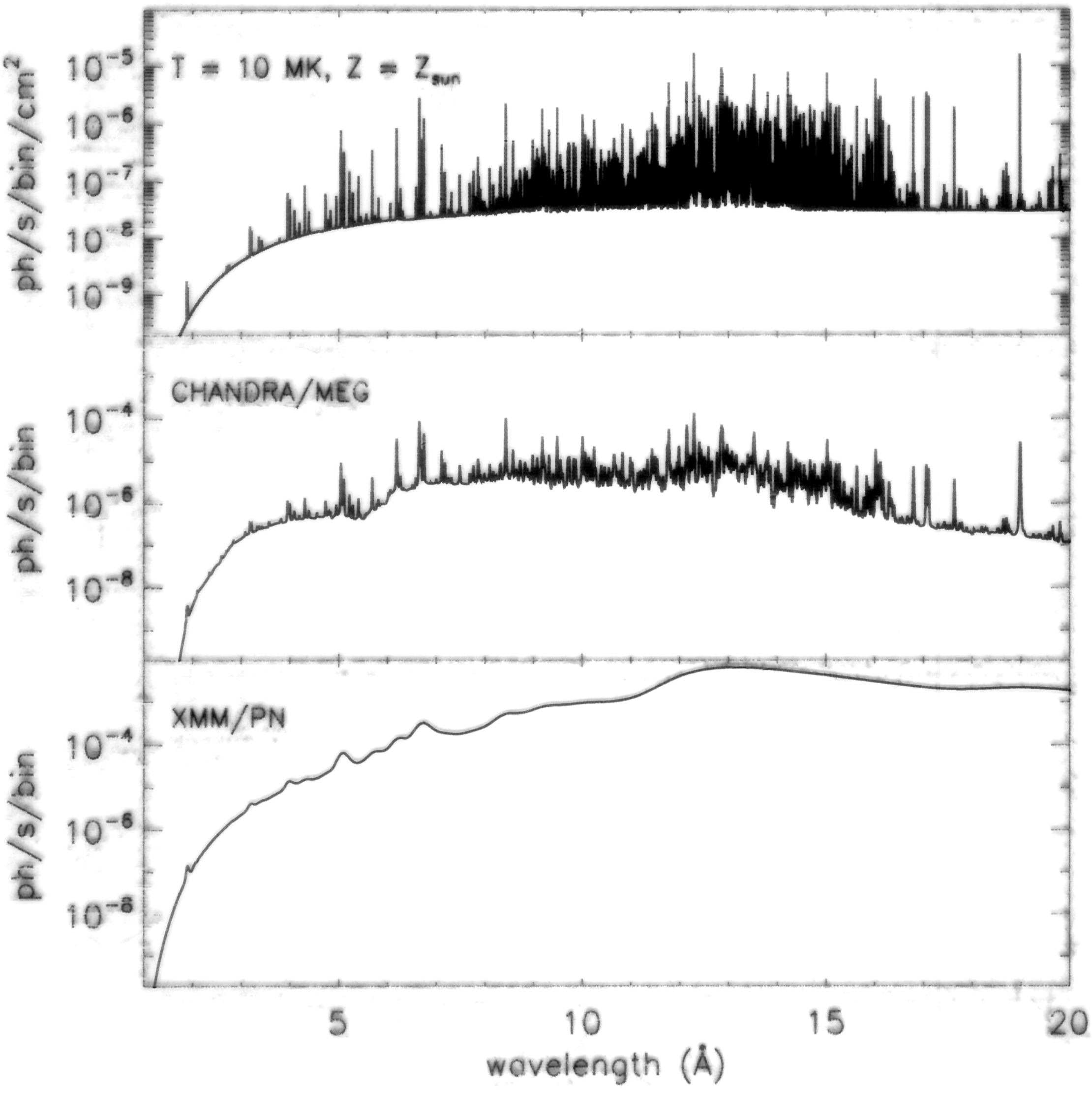
- PUT EVERYTHING IN A MANAGEABLE SYSTEM ...

VERY POWERFUL TOOLS OF SYNTHESYS

- Raymond and Smith → APEC
- Landini e Monsignori Fossi → CHIANTI
- Mewe & Gronenschild
- Mewe, Kaastra, Liedhal (MEKAL) → SPEX
- Arnaud & Rothenflug

etc.

APEC




$S(T, E)$

$F_{C,M}(T, E)$

$F_{XP}(T, E)$

Thanks to C. Argiroffi

# SPECTRAL MODEL

$$S(T,E) = \underbrace{S_{Bs}(T,E)}_{\text{Bremss}} + \sum_k \underbrace{S_{\ell_i}(T,E_k)}_{\text{LINES}} + \sum_\ell \underbrace{S_{Rec}(T,E_\ell)}_{\text{Recomb.}} + \sum_m \underbrace{S_{2p}(T,E_m)}_{\text{2 photon}}$$

at a given plasma Temperature
Emission at various photon Energies $E$
Per unit emission measure $\left( EM = \int n_e^2 \, dV \right)$

Detected in the instrument focal plane

$$D(T,E') = \int dE \; M(E',E) \; A(E) \; S(T,E) \cdot n_e^2 V$$

$M(E',E)$ = Detector response matrix: prob. that a photon of energy $E$ is detected in bin of energy $E'$

$A(E)$ = instrument effective Area vs $E$

what is in previous graphs

# REAL SOURCES ?

$$R(E') = \int dE \; M(E',E)\, A(E) \int dV_T \; n_e^2(T)\; S(T,E) =$$

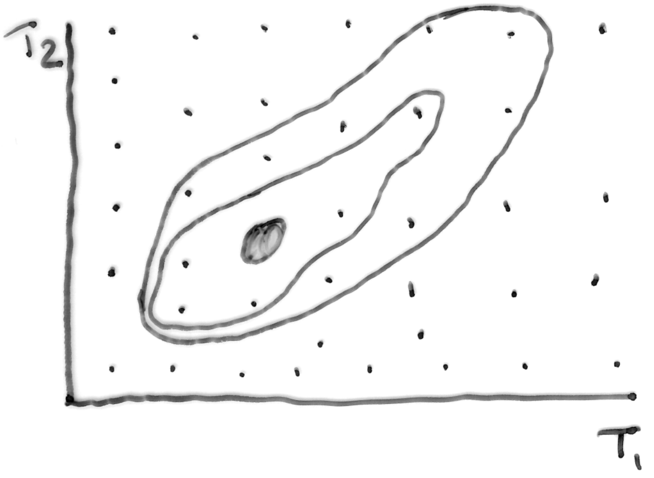
$$= \int dE \; M(E',E)\, A(E) \int dT \; S(T,E) \boxed{\frac{n_e^2(T)}{dT/dx} \cdot A(T)}$$

diff. em. measure
at T

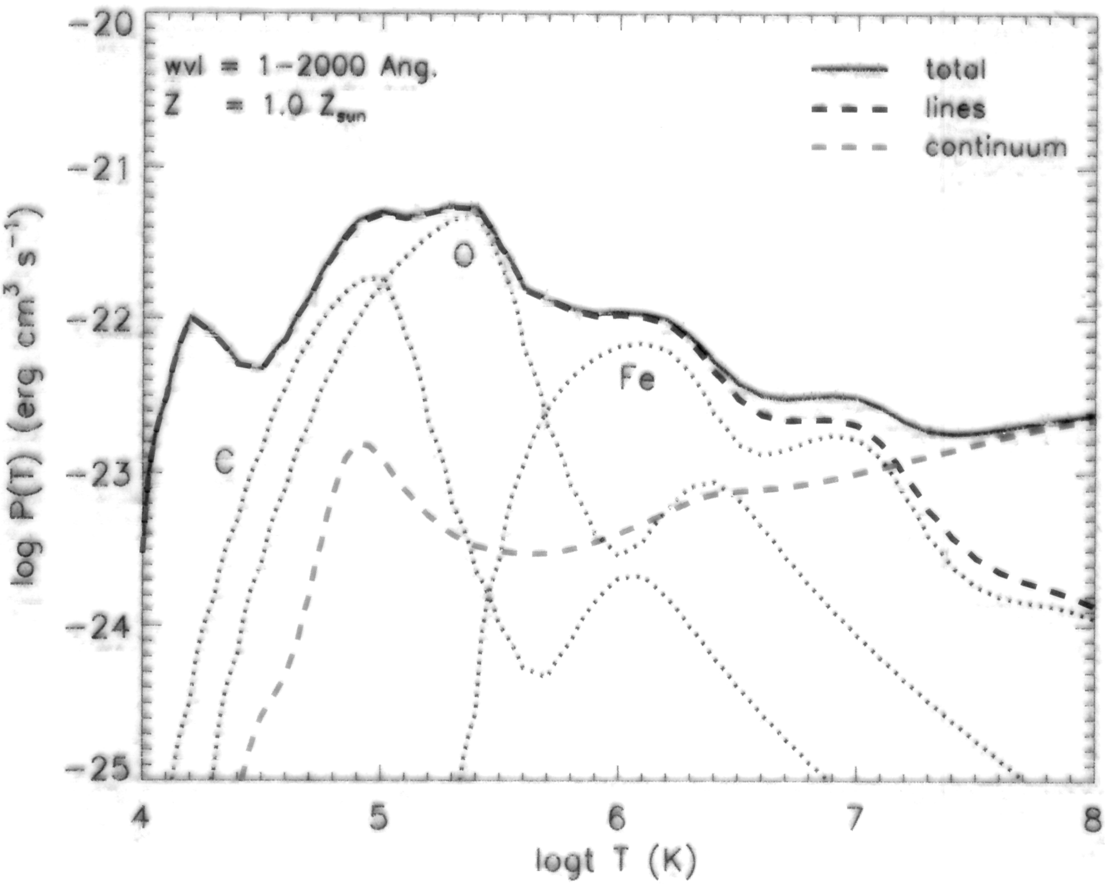
Deriving the Differential emission measure
or the emission measure at various T's
is a major task of data analysis

INVERTING THE ABOVE INTEGRAL IS HOPELESS
(Numerically unstable Brown (1973))

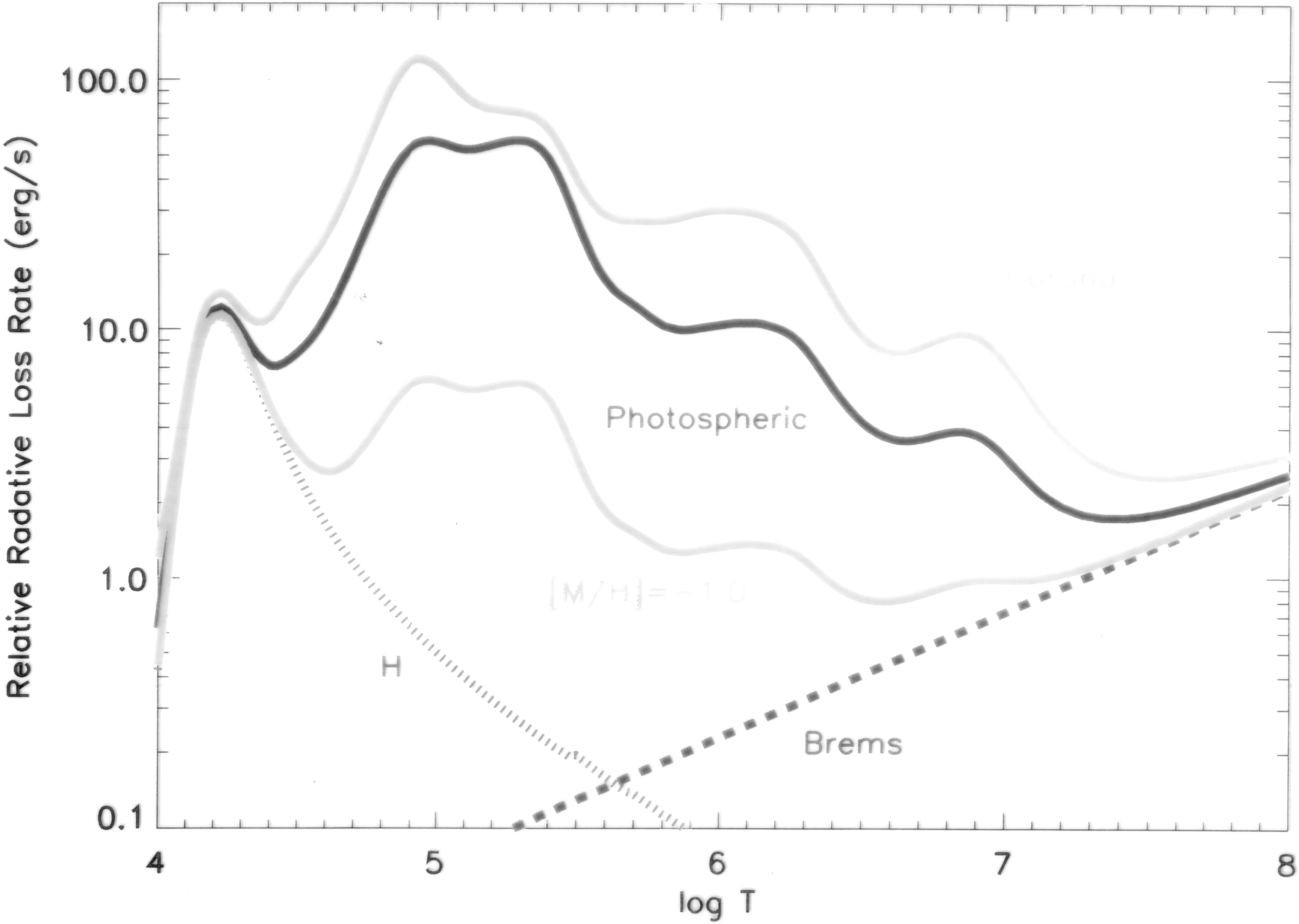
Other approach: forward modeling




grid of models for diff. combination of model parameters (e.g. 2T) and find the one which best fits


wvl = 1-2000 Ang.
Z = 1.0 Z_sun
total
lines
continuum
O
C
Fe
-20
-21
-22
-23
-24
-25
log P(T) (erg cm^3 s^-1)
4
5
6
7
8
logt T (K)

## Radiative Loss Rates for "Photospheric" and "Coronal" Abundances



# X-RAY EMISSION FROM SHOCKS

TWO MAIN CASES

- ACCRETION SHOCKS
- SHOCKS AT THE TIP OF PROTOSTELLAR JETS