SPECTRAL FORMATION IN GALACTIC X-RAY SOURCES

Richard McCray
Joint Institute for Laboratory Astrophysics
University of Colorado and National Bureau of Standards
Boulder, Colorado 80309

ABSTRACT

Theories for the formation of the spectra of galactic X-ray sources are reviewed, emphasizing the mechanisms for production of atomic emission lines and the interpretation of their observations. Three classes of idealized source models are discussed. The first is a "coronal model," in which electron collisions control the ionization and emissivity of the gas. When departures from ionization equilibrium in a shock are included, such models may describe the X-ray emission from a supernova remnant. The second is a "nebular model" of a distribution of gas around a compact source of continuum X-rays, in which photoionization and recombination in the surrounding gas cloud dominate the spectral formation. The third is a "diffusion model," a variant of the nebular model in which the opacity is so great that electron scattering plays a significant role in spectral formation. The latter two models describe aspects of spectral formation in binary X-ray sources.

To be published in Galactic X-Ray Sources, ed. P. Sanford, Proceedings of NATO Advanced Study Institute, Cape Sounion, Greece, June, 1979 (Wiley).

---

1. INTRODUCTION

Thanks to X-ray telescopes with improved spectral resolution, such as the proportional counters on Ariel V, OSO-8, and HEAO-1, and most recently the solid state and crystal spectrometers on the Einstein Observatory, we now know that galactic X-ray sources of all kinds show features in their X-ray spectra due to atomic transitions of abundant elements such as Si, S, and Fe. For details, see the article by Steve Holt in this volume. Analysis of these spectra permits determination of physical characteristics of the emitting region — such as density, temperature, element abundances, and velocity — impossible to infer from X-ray photometric data alone. As our technical capability advances toward higher sensitivity and spectral resolution, we can expect that the X-ray spectra will reveal the kind of information about compact objects and supernova remnants (SNRs) that optical spectroscopy has extracted from the spectra of stars and nebulae.

However, as with optical light, the X-rays do not arrive at earth with the desired information coded in a handy and familiar format, such as binary or octal. Instead, the physical information is encoded into the X-ray spectrum through a complex network of atomic processes and radiative transfer. Therefore, in order to utilize the information we receive, we require a theory to "decode" the X-ray spectra. The development of such theory has been a lively activity in recent years.

---

As discussed in the article by Professor Trümper, X-ray spectral features may also be produced by quantized cyclotron transitions in the very strong magnetic field at the surface of a neutron star. Here I shall not discuss this fascinating topic. Instead, I shall concentrate on the formation of X-ray spectra in atomic transitions, for which the relevant physical processes are somewhat better understood.
In the coronal model, the emergent spectrum is dominated by emission lines excited by electron collisions. Typically, the strongest X-ray emission lines from each abundant element (except Fe) are the \( \left(2^3p_1, 2^3p_1, 2^5S_1 + 1^5D_0\right) \) triple systems of the helium-like ions, with the Ly lines of the hydrogenic ions somewhat weaker. With sufficient spectral resolution \((\lambda/\Delta\lambda \approx 100)\) to resolve the triple systems, it should be easy to verify whether collisional excitation is dominant, because the relative emission line strengths should be proportional to the collisional excitation rates.

As Gabriel and Jordan (1969a,b) and Allentoth, Drake and Tucker (1972) have described, the forbidden, \( \bar{2}^3S \), member of the helium-like triple system may be used as a density diagnostic, since it is suppressed in favor of the \( \bar{2}^3P \) intercombination line by electron collisions at electron densities \( n_e \gtrsim 0.6 \times 10^{12} \text{ cm}^{-3} \), where \( Z \) is the nuclear charge of the relevant ion.

The emergent X-ray line spectrum is calculated from an expression of the form

\[
L_\nu = EM \frac{1}{\lambda} A_\lambda G_\lambda (\nu, T) \quad (2)
\]

where

\[
G_\lambda (\nu, T) = \sum_{j<k} f_{jk}^{(1)}(T) c_{jk}(T) h\nu_{jk} \quad (3)
\]

where the \( c_{jk}(T) \)'s are rate coefficients for excitation of level \( k \) of each ion by electron collisions and where \( EM = \int n_e^2 dV \) is the volume emission measure. Note that the spectral shape is determined entirely by the assumed element abundances, \( A_\lambda \), and the temperature. Figure 1, taken from Shapiro and Moore (1976), shows a typical coronal spectrum for standard cosmic abundances. Note that it is dominated by emission lines. It is common practice in X-ray astronomy to determine \( A_\lambda \), \( T \), and \( EM \) by varying these parameters until the resulting coronal model best fits the observed spectrum. If no combination of \( A_\lambda \) and \( T \) produces an acceptable fit, one might try a composite of two or more regions with different emission measures and temperatures. By allowing such flexibility, it is always possible to find some combination of coronal model parameters that fits an observed spectrum arbitrarily well.

An important caveat concerns the accuracy of the atomic physics that goes into the theory. Because very few of the relevant collisional excitation and ionization rate coefficients are known experimentally, we must rely largely on theoretical calculations. Thus, abundance determinations based on X-ray emission line ratios are no more accurate than the approximate theoretical rate coefficients for the emitting ions, which may differ from the true rates by a factor of up to 3. It is possible to obtain more accurate theoretical results (say, within \( \pm 20\% \)), but this requires laborious calculations that have been performed for only a few selected ions.

Another important caveat concerns the use of the coronal model in situations where it is not really applicable — in particular, in the case of SNR's. An assumption built into the coronal model is that the ionization of the elements is determined by a stationary local balance between ionization and recombination. While this is probably a good approximation for the solar corona and for gas in clusters of galaxies, where flow times should be long compared to recombination times, it most likely breaks down in supernova shells, in which a blast wave propagates into interstellar gas. Even in the idealized case of a SNR propagating into a uniform medium, the shocked gas has a rapidly changing temperature profile, and the elements do not reach the stationary ionization balance determined by the local post-shock temperature. Changes in ionization level tend to lag changes in temperature. If radiative cooling is dynamically negligible, as is likely in a young hot SNR, the elements in gas at a given temperature are likely to be less ionized than the
III. THE NUCLEAR MODEL

A better model for the X-ray emission from a shock can be constructed by integrating the coupled ionization and collisional rate equations (1)-(3), together with the hydrodynamic equations of the shocked gas. The model would be particularly valuable for fitting normal models to the X-ray spectra of SNe II, using the shock velocity instead of the gas temperature as one of the fitting parameters (the other being element abundances). It would be particularly interesting to see how the best-fit element abundances depend on the choice of model (normal or shock).

With improved spectral resolution we can obtain direct evidence of the local electron temperature from the ratio of emission line strengths of ionized species. This can be inferred from the intensities of satellite lines, found on the low-frequency side of emission lines of ions with two or more electrons. These transitions are more sensitive than collisional excitation of the same ions.

The spatial distribution of the emergent X-ray spectrum is not a free parameter, but is determined by the absorption and emission of the radiation. The structure of the ionized gas is dominated by photoionization, not electron collisions and the formation of the emergent X-ray spectrum.
dominated by photoabsorption, radiative recombination, and fluorescence, rather
than by collisional excitation.

Assuming a stationary local balance between ionization and recombination,
we determine the ion densities $n_1^j(r)$ by equations of the form

$$
\begin{align*}
\frac{d}{dr} n_1^j(r) & = J_1^j(r) \int du \frac{J_1^j(u)}{hv} \sigma_1^{j'}(v) a_1^{j'} + n_1^{j+1}(r) n_e(r) a_1^{j+1}(T) \\
- n_1^j(r) & \left( J_1^j(r) \int du \frac{J_1^j(u)}{hv} \sigma_1^{j}(v) + n_e(r) a_1^{j}(T) \right) = 0
\end{align*}
$$

where $J_1(v, r)$ is the mean intensity of the radiation field, the $\sigma_1^{j'}(v)$'s are
photoionization cross sections, and the $a_1^{j'}$'s are Auger yields, giving
the fractional probability that an ion in stage $j'$ will relax to stage $j$
following the creation of an inner shell vacancy by X-ray photoionization. Typically,
creation of a K-shell vacancy will be followed by the emission of a few Auger
electrons.

The coupled set of equations (4) are solved together with an energy
equation, expressing the condition that the luminosity of radiation emitted at
given place equals that absorbed. Thus, in this model the temperature $T(r)$
is part of the solution.

The mean intensity, $J_1(v, r)$, is determined by an equation of transfer, with
absorptivity and opacity being functions of $n_e(r)$, $n_1^j(r)$, and $T(r)$. However, in
some environments these coefficients are small enough to be neglected. This
permits a great simplification — the optically thin approximation: $J_1(v, r) =
L_\xi(v)/4\pi r^2$. Then, the solutions of the coupled set of equations (4) can be
expressed in the form $n_1^j = L_1^j(\xi)$ and $T(r) = T(\xi)$, where $\xi \equiv L/4\pi r^2$.
The functional dependences on $\xi$ depend sensitively on the shape of the input

spectrum, $g(\nu)$, but once calculated they may be used to describe a great
variety of environments using this simple scaling law.

When the opacity of the surrounding gas becomes important, the transfer
equation for $J_1(r)$ must be solved, making the theory much more complicated.
However, the equations can be solved to a reasonable level of accuracy by
making suitable approximations to the transfer equation. Hatchett et al.
(1976) use an "outward-only integration" approximation, which is known to give
a reasonably accurate description of a planetary nebula. For a given source
spectrum, $g(\nu)$, the resulting ionization and temperature no longer depend only
on the single parameter, $\xi$, but also on a second "opacity parameter," $q$. In
the case of a constant density gas cloud, $q = L/\xi$.

The temperature and ionization structure and the emergent X-ray spectrum
of a nebular model are very different from those of the coronal model.
Because photoionization dominates collisional ionization, highly ionized atoms
tend to be found at a much lower temperature than in the coronal model.
For example, according to the coronal model oxygen is mostly hydrogenic at a
temperature $T \sim 10^5$ K, whereas in a typical nebular model oxygen is mostly
hydrogenic at $T \sim 10^4$ K. Because the ions are at low temperature, collisional
excitation is a much less important radiation mechanism; instead, recombination
and fluorescence lines dominate the emission spectrum.

The latter process, X-ray fluorescence, is particularly important in the
case of iron K lines. When an X-ray with $hv \gtrsim 8$ keV creates a K-shell vacancy
in an iron ion with three or more electrons, the excited ion has a substantial
probability of emitting a $K_\alpha$ fluorescence photon. The energy of the $K_\alpha$
photon depends on the particular transition and ionization stage, and ranges from
$6.40$ keV for $Fe^{2+}$ to $6.65$ keV for $Fe^{23}$. Iron is unique among the abundant
elements in having a large fluorescence yield, $\gamma \approx 302$; elements such as O,
A second application of the method is the prediction of some of the electric properties of the racemate of 1,2-diaminocyclohexane (1761). According to calculations by Kallay and Kricheff (1761), the electric properties of the racemate are influenced by the electric properties of the individual enantiomers. In addition to the electric properties, the optical rotation of the racemate is also influenced by the electric properties of the individual enantiomers. The calculations by Kallay and Kricheff (1761) are in agreement with the experimental results of other investigators.

For studying the electric and optical properties of the racemate, a potential goal is to have a better understanding of the intermolecular interactions. This can be achieved by calculating the electric properties of the racemate using quantum chemical methods. The calculations can be performed using density functional theory (DFT) or semi-empirical methods. The results of these calculations can then be compared with the experimental results to gain a better understanding of the intermolecular interactions.

The electric properties of the racemate are influenced by the electric properties of the individual enantiomers. The calculations by Kallay and Kricheff (1761) show that the electric properties of the racemate are different from those of the individual enantiomers. This is because the enantiomers have different electric properties, which affect the electric properties of the racemate.

The optical rotation of the racemate is also influenced by the electric properties of the individual enantiomers. The calculations by Kallay and Kricheff (1761) show that the optical rotation of the racemate is different from that of the individual enantiomers. This is because the enantiomers have different optical rotations, which affect the optical rotation of the racemate.

In conclusion, the electric properties and optical rotation of the racemate can be influenced by the electric properties of the individual enantiomers. The calculations by Kallay and Kricheff (1761) are in agreement with the experimental results of other investigators. Therefore, the calculations by Kallay and Kricheff (1761) can be used to gain a better understanding of the intermolecular interactions.
When electron scattering becomes important, the techniques used to calculate the structure of nebular models break down, and we must consider the spatial diffusion of X-rays. Furthermore, we must consider the effects of "Comptonization," the modification of the X-ray spectrum by electron scattering. This process, usually insignificant in the formation of optical spectra, becomes important for X-ray spectra for two reasons: first, because photoelectric cross sections decrease rapidly above threshold (\(\sim 1\)), electron scattering can be the dominant opacity for hard X-rays; second, the fractional energy shift of a photon upon electron scattering is of the order \(2\times 10^{-3}\) for a 10 keV X-ray, but \(\sim 10^{-3}\) for an optical photon (typically formed where \(T \lesssim 10^6\) K).

Because of the importance of Comptonization in the formation of X-ray spectra, considerable effort has been devoted during the past few years to the development of theories capable of accurately describing its effects. There are at least four distinct kinds of models in which Comptonization has qualitatively different consequences. The first is that of a cool source of relatively soft photons surrounded by a distribution of very hot gas. At temperatures greater than \(10^8\) K, radiative processes become so inefficient that the gas becomes "photon-starved." In this case, the emergent X-ray spectrum may be dominated by the hardening of photons from the cool source as they propagate through the hotter gas. The result is a hard continuum spectrum that may resemble a power law (Sunyaev and Titarchuk 1979). Such models have been proposed to explain the X-ray spectra of quasars (Katz 1976) and of accretion disks around black holes (Shapiro et al. 1976).

The second model is a variant of the first in that soft photons are hardened by Comptonization in a gas of very high temperature. However, in this case the source of soft photons is presumed external, and the hard spectrum is created by diffuse reflection of the soft photons by the hot gas.
The current theory of adaptation to changes in the environment is based on the concept of a complex, non-linear system that can adapt to changes in its environment. This system is characterized by the presence of feedback loops, which allow it to adjust its behavior in response to external stimuli. The theory suggests that the system can adapt to changes in a variety of ways, including through the modification of internal parameters, the addition of new components, or the removal of existing ones. The key to this adaptation is the ability of the system to learn from its environment, and to use this learning to make predictions and decisions that are optimized for future outcomes. The theory of adaptation is a powerful tool for understanding the behavior of complex systems, and it has applications in a wide range of fields, from biology to economics.
The approximation of a passive medium is probably a good one for this model, because the presumed stellar wind is sufficiently dense and extended that heating and ionization by the X-ray source should not substantially alter its properties.

The second technique for describing Comptonization is the use of a frequency diffusion (Fokker-Planck) approximation; this results in the famous equation of Konpaneets (1957). The Konpaneets equation is non-linear, having a term proportional to the square of the photon intensity to describe induced Comptonization; but this non-linear term is usually unimportant for the case of X-rays, which are likely to be very dilute. Ross, Weaver and McCray (1978) have shown that the Konpaneets equation should be modified to describe accurately the Comptonization of X-rays by low temperature electrons. The resulting equation can be incorporated into a spatial diffusion equation, including line emission and photoelectric absorption. This equation can then be solved together with ionization rate equations and an energy balance equation, to give a comprehensive description of the radiative transfer of X-rays through an optically thick distribution of gas. Such solutions have been generated by Ross et al. (1978) and by Ross (1979).

Figure 4, taken from Ross et al. (1978), illustrates the formation and Comptonization of iron lines in a model consisting of a dense \( n_e = 10^{16} \text{ cm}^{-3} \) spherical shell of gas with \( T_e = 6 \), surrounding a compact source of continuum X-rays at a radius \( R = 7 \times 10^8 \text{ cm} \). The dashed curve is the source spectrum, presumed to be an exponential with \( kT_x = 40 \text{ keV} \) and luminosity \( L = 10^{37} \text{ erg s}^{-1} \). The shell is assumed to have a temperature \( T = 10^7 \text{ K} \), but its ionization is calculated self-consistently. The dotted curve shows the spectrum that emerges when Comptonization is neglected in the theory. Strong photoelectric absorption by iron is evident in the range 8-30 keV. The absorption profile is complex because it is caused by many ions of iron, each of which has a different photoelectric threshold, and because it is contaminated by recombination continuum emission. Weaker photoabsorption due to other elements such as Si, S, etc., is evident below 5 keV. Very strong emission lines due to recombination of hydrogenic and helium-like ions of iron are also evident.

The solid curve in Figure 4 is the spectrum which emerges when Comptonization is included. Three pronounced effects are evident: first, the high energy photons are degraded by Comptonization, greatly suppressing the high energy tail of the emergent spectrum; second, the photoelectric absorption is largely filled in; and third, the strong emission lines are merged and spread into a broadened and skewed profile. A few photons do escape in narrow line cores without Comptonization. The narrow core of emergent La photons is weaker than that of the helium-like ions because the La photons are emitted in the inner, more ionized, part of the shell, at a greater scattering optical depth from the surface.

It follows that when the electron scattering optical depth is substantial, accurate inferences cannot be made from the observed spectrum without allowing for the effects of Comptonization. For example, consider the interpretation of the observations of strong iron K absorption in the spectrum of GX 391-2 (Swank et al. 1976). If Comptonization is neglected, fitting a simple photoelectric model to the observed spectrum implies \( \tau_e \geq 1 \), assuming a normal cosmic abundance of iron. But if so, the actual photoelectric absorption has probably been partially filled in by Comptonization, implying more absorbing matter than originally inferred.

The model of a compact X-ray source surrounded by a spherical shell may be of use in understanding the soft X-ray emission from Her X-1. The brightness of this soft X-ray emission implies the presence of dense gas with \( \tau_e \geq 1 \) at a
The effect of the correct models are very complex. The correct models indicate that different effects have different effects on the correct models. The correct models are very complex, the correct models indicate that different effects have different effects on the correct models. The correct models are very complex, the correct models indicate that different effects have different effects on the correct models. The correct models are very complex, the correct models indicate that different effects have different effects on the correct models. The correct models are very complex, the correct models indicate that different effects have different effects on the correct models.
REFERENCES


——— 1979, Ibid., 31, 541.


Figure Captions

Fig. 1. Theoretical X-ray emission spectrum from an optically thin coronal model with gas temperature T = 10^6 K. Emission lines are plotted with full width at half maximum of 5 Å (from Shapiro and Hora, 1976).

Fig. 2. Theoretical X-ray spectrum for a nebular model of a compact source of continuum X-rays with luminosity L = 10^7 ergs/s, surrounded by a spherical gas cloud of atomic density n = 10^4 cm^-3 and radius R = 1.0 x 10^2 cm. Emission lines and recombination continua are plotted with a resolving power λ/Δλ = 100 (from Batchett et al., 1976).

Fig. 3. Model for variable soft X-ray absorption due to a stellar wind in a binary X-ray source. The dashed circle indicates the spherical zone where oxygen is almost fully ionized and does not photoabsorb X-rays. The angle φ is the inclination of the binary system, and the angle ψ is the orbital phase. The ray from the X-ray source to earth traces out the cone during the binary period. X-ray photoabsorption by oxygen occurs beyond the dashed circle, and is greatest near the star, where the wind density is greatest. The zones where other elements photoabsorb X-rays have similar geometry but different sizes.