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NONEQUILIBRIUM IONIZATION MODELS FOR ANALYSIS OF X-RAY SPECTRA OF SUPERNOVA REMNANTS

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RESUMEN

Las remanentes de supernova (SNRs) son de los objetos más brillantes en rayos-X que serán observados por los nuevos satélites de rayos-X (*Chandra*, *XMM* y *Astro-E*). La emisión térmica de las SNRs no puede ser analizada con los códigos usuales de emisión de rayos-X porque el plasma de estos objetos no está en equilibrio de ionización. Se necesitan modelos de ionización fuera de equilibrio (NEI) para sacarle provecho a los datos venideros de alta calidad sobre SNRs. Presento un conjunto básico de modelos NEI para el análisis de espectros de rayos-X de SNRs; modelos con temperatura constante, con escalas temporales de ionización únicas y generalizadas, choques plano paralelos con temperatura electrónica constante y modelos de Sedov con temperaturas diferentes para iones y electrones.

ABSTRACT

Among the brightest sources of X-ray emission are supernova remnants (SNRs), which will be extensively observed by new X-ray satellites (*Chandra*, *XMM*, and *Astro-E*). Thermal X-ray emission from SNRs cannot be analyzed with standard X-ray plasma codes, because plasmas in these objects are not in ionization equilibrium. Nonequilibrium ionization (NEI) models are necessary in order to take advantage of the anticipated flood of high quality X-ray data on SNRs. I present a basic set of NEI models for analysis of thermal X-ray spectra of SNRs: constant-temperature, single ionization timescale models, generalized single ionization timescale models, plane-parallel shocks with constant electron temperature, plane-parallel shocks and Sedov models with unequal ion and electron temperatures.

Key Words: **SUPERNOVA REMNANTS — X-RAYS: ISM**

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1. MODELING THERMAL X-RAY EMISSION FROM SUPERNOVA REMNANTS

X-ray astronomy has advanced significantly in recent years because of improved X-ray instrumentation. In the field of SNRs, this has led to many advances, such as the discovery of the nonthermal synchrotron X-ray emission produced by energetic electrons accelerated at a shock front, identification of a number of new neutron stars and associated synchrotron nebulae, discovery of new SNRs, and identification of young, ejecta-dominated SNRs. Spatially-resolved X-ray spectroscopy, provided by the *ASCA* satellite, played a crucial role in these discoveries. The *ASCA* database now contains a large number of excellent spectra of SNRs. Observations with the next generation of X-ray satellites (*Chandra*, *XMM*, and *Astro-E*) will provide even better quality data, ensuring continuing progress in the SNR research.

While the new X-ray observations led to a significant progress, X-ray spectral data on SNRs, and *ASCA* data in particular, have been mostly underutilized. The fundamental reason for this unsatisfactory situation is that X-ray emitting plasmas in SNRs are not in ionization equilibrium, significantly complicating analysis of their X-ray spectra. Most X-ray observers do not even have access to simple nonequilibrium ionization (NEI) models. The simplest NEI model consists of an impulsively heated, uniform and homogeneous gas, initially cold and neutral. While this model is often used in analysis of X-ray spectra of SNRs, in most cases it is unlikely to be a good approximation to shock-heated plasmas in SNRs. The best choice for general NEI models

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are idealized hydrodynamical structures, such as the Sedov-Taylor self-similar solution describing a point blast explosion in a uniform ambient medium.

X-ray emission calculations based on the Sedov dynamics have been performed numerous times in the past, with the most extensive set of calculations presented by Hamilton, Sarazin, & Chevalier (1983). Sedov models were successfully used in X-ray spectral modeling of SNRs in the Large Magellanic Cloud (Hughes, Hayashi, & Koyama 1998). But the progress has been slow because of technical difficulties in constructing a robust NEI package for use by the general X-ray community. This unfortunate situation is improving, beginning with Sedov models and a number of simpler NEI models based on an updated Hamilton & Sarazin spectral code. In particular, modeling of the prominent Fe L-shell complex near 1 keV is based on atomic calculations by Liedahl, Osterheld, & Goldstein (1995). These NEI models, briefly described below, will be included in the next release of the XSPEC software package.

2. NONEQULIBRIUM IONIZATION MODELS

Constant Temperature, Single Ionization Timescale Model — parameters: temperature T (keV), heavy-element abundances, ionization age $\tau = n_e t$ (s cm^{-3}), redshift. The simplest NEI model consists of an impulsively heated, uniform and homogeneous gas with electron density n_e, initially cold and neutral. In most cases, this constant temperature, single-ionization timescale model is too simple to provide an adequate description of SNR spectra.

Generalized Single Ionization Timescale Model — parameters: temperature T (keV), heavy-element abundances, ionization age τ (s cm^{-3}), ionization timescale-averaged temperature $\langle T \rangle$ (keV), redshift. This is a generalization of the simplest NEI model just discussed, where temperature is allowed to vary with time. This single-ionization timescale model should also be used with caution in analysis of X-ray spectra of SNRs.

Constant-Temperature, Plane-Parallel Shock — parameters: temperature T (keV), heavy-element abundances, ionization age τ (s cm^{-3}), redshift. This is a plane-parallel shock model with a constant postshock electron temperature T and with ionization age $\tau = n_e t$, where n_e is the postshock electron temperature and t is the shock age. This model differs from single ionization timescale models in its linear distribution of ionization timescale vs. emission measure (at the shock front ionization timescale is 0, and attains maximum τ for the material shocked first). In a limited range of photon energies, plane-parallel shocks might serve as useful approximations to Sedov models with high electron temperatures.

Plane-Parallel Shock with Collisionless and Coulomb Heating — parameters: mean shock temperature T_s (keV), postshock electron temperature T_{es} (keV) immediately behind the shock front, heavy-element abundances, ionization age τ (s cm^{-3}), redshift. It is likely that electrons are not fully equilibrated with ions in collisionless shocks in SNRs. Because the ion temperature is then larger than the electron temperature, electrons are heated by Coulomb collisions with ions in the postshock plasma. This leads us to a more general type of a plane-parallel shock, where the postshock electron temperature T_{es} depends on the amount of collisionless electron heating at the shock, but it is less than or equal to the mean gas temperature T_s. In the postshock region, Coulomb collisions gradually lead to increase in the electron temperature T_e, which becomes equal to T_s for a large shock ionization age τ, far from the shock front.

Spatially-Integrated Sedov Model — parameters: the same as in the plane-parallel shock with Coulomb heating. This is a spherical blast wave described by the Sedov dynamics, with both collisionless and Coulomb heating of electrons. This model should be routinely used in analysis of SNR spectra.

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