



11: X-ray Astronomy

- X-rays are generated by extreme processes
 - thermal: blackbody ($>10^6$ K), bremsstrahlung, spectral lines from inner electrons
 - non-thermal: synchrotron, inverse Compton
- X-rays experience photo-electric absorption in the interstellar medium
 $F = F_0 \cdot e^{-\sigma N_H}$, where σ = photo-ionisation cross-section, N_H = hydrogen column
- Current X-ray observatories: *RXTE*, *XMM*, *Chandra*, *Suzaku*
- X-ray imaging: collimator, coded mask, grazing incidence mirror
- X-ray spectra: CCD, transmission grating, calorimeter
- X-ray spectroscopy: fold model spectrum through effective area curve of mirror and of detector to compare with and fit to data



14: SNe, SNRs & Neutron Stars

- Core-collapse supernova: iron core, $p^+ + e^- \rightarrow n$, envelope bounces off core, explosion
 - 10^{46} J in neutrinos; 10^{44} J in kinetic energy of stellar ejecta
- Optical light curve driven by radioactive decay: main isotopes seen are ^{56}Co , ^{57}Co , ^{44}Ti
- Supernova remnants:
 - synchrotron (radio, X-rays), bremsstrahlung from 10^6 K gas (X-rays), emission lines from cooling dense clumps (optical)
 - free expansion, $R \propto t$; Sedov phase, $R \propto t^{2/5}$; radiative phase, $R \propto t^{1/4}$
 - dissipation when $V_{\text{shock}} < c_{\text{sound}}$, after approx 3 million years
- Neutron stars: mass $\approx 1.4 M_{\text{sun}}$; radius $\approx 10\text{-}12$ km; surface temperature $\approx 10^6$ K
 - born with surface fields $|B| \sim 10^{12} - 10^{15}$ G and rotation periods $P \sim 10\text{-}60$ ms
 - stability of rotation allows precision measurement of times of arrival $\rightarrow P, dP/dt$
 - all pulsars slowing down via magnetic dipole braking
 - energy lost via relativistic wind, produces synchrotron-emitting “pulsar wind nebula”

- Pulsar spin-down:
$$B = 3.2 \times 10^{19} \left(\frac{-\dot{\nu}}{\nu^3} \right)^{1/2} \text{ G} \quad \tau = -\frac{\nu}{2\dot{\nu}} = \frac{P}{2\dot{P}}$$



18: Particle Acceleration, Gamma-ray Astronomy and Cosmic Rays

- Cosmic rays: gyroradius $r_g = \frac{p}{eB} \approx 10^{-3} E_{10^{12} \text{ eV}} B_{\mu G}^{-1} \text{ pc}$
 - low energy: Galactic, wander in magnetic fields, direction lost
 - high energy: can escape disk of Milky Way; must be extragalactic
- Cosmic ray detection: air showers produce electrons, muons & gamma-rays
- Maximum energy of cosmic rays accelerated in SNR shocks
 - determined by lifetime, rate of escape, radiative losses
 - radio synchrotron in SNRs implies $E_e \sim 10^9 \text{ eV}$; X-ray synch. implies $E_e \sim 10^{14} \text{ eV}$
 - γ -rays from neutral pions: would be direct evidence for proton acceleration in SNRs
 - γ -rays from inverse Compton scattering: additional evidence for e^- accel. in SNRs
- Other evidence for proton acceleration in SNR shocks
 - lower shock temperature seen in X-rays than predicted from expansion speed
 - forward shock & reverse shock closer together than expected
- Three mysteries regarding ultra-high energy cosmic rays ($E > 10^{20} \text{ eV}$)
 - distribution seems isotropic, but at these energies, should be no magnetic deflection
 - “GZK cutoff”: CMB produces pion decay above $5 \times 10^{19} \text{ eV}$; distance limit $\sim 50 \text{ Mpc}$
 - energetic sources needed; “Hillas plot” constrains size & B of likely accelerators