



# 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  $\sigma$  = 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  $^{56}\text{Co}$ ,  $^{57}\text{Co}$ ,  $^{44}\text{Ti}$
- 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  $r_g = \frac{p}{eB} \approx 10^{-3} E_{10^{12} \text{ eV}} B_{\mu\text{G}}^{-1} \text{ pc}$ 
  - 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  $E_e \sim 10^{14} \text{ eV}$
  - $\gamma$ -rays from neutral pions: would be direct evidence for proton acceleration in SNRs
  - $\gamma$ -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