Compact galactic sources of cosmic radiation

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Summary

1. Pulsar emission
2. Crab nebula
3. Pulsar wind model
4. Neutron stars with ultra-strong magnetic fields

1. Pulsar emission

a) Pulsar energy output

Standard radio-pulsars

- rotating neutron stars, periods $P \sim 10ms - 1s$,
- mass $M \sim 1M_{\odot}$,
- spin-down rates $\dot{P} \sim 10^{-11} - 10^{-14} ss^{-1}$,
- magnetic field $B \sim 10^{12}G$.

Spin-down luminosity

$$\dot{E} \equiv \dot{E}_{rot} = I\omega\dot{\omega} \sim 10^{35} - 10^{39} ergs^{-1}$$

- the moment of inertia, $I \sim 10^{45} gcm^2$, from neutron star models,

- values: $\dot{E} \sim (10^2 - 10^6) L_\odot$, brightest stars: $L \sim 10^6 L_\odot$

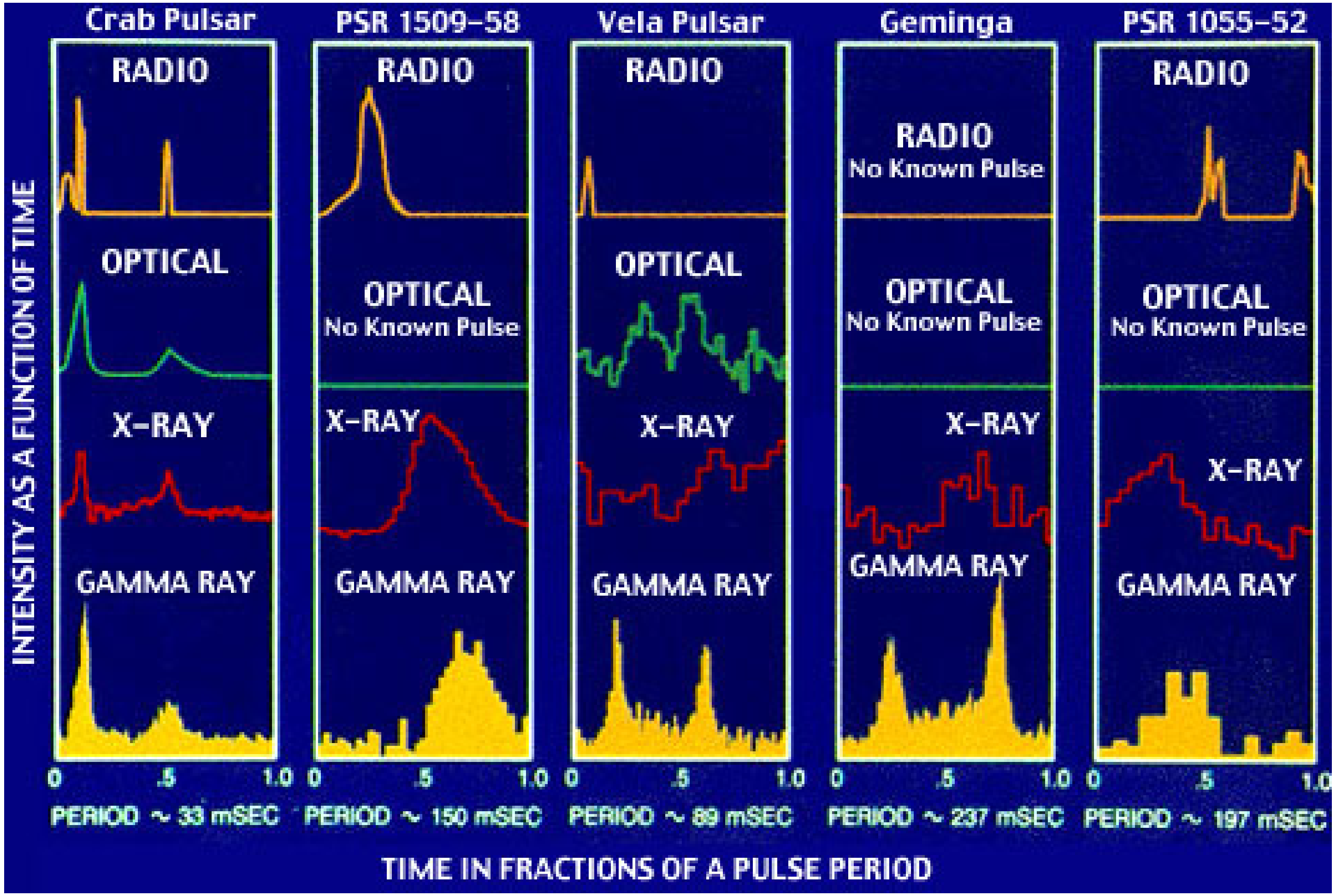
- total rotational energy of a young pulsar: $E_{rot} \sim 10^{51} erg$

Pulsars are powerful galactic emission sources,

(young neutron stars cool by thermal neutrino and photon emission, E_{int} decreases)

b) Nature of pulsar emission

- detected in a broad range of electromagnetic radiation: radio, optical, X-rays, γ-rays



Crab Pulsar
PSR 1509-58
Vela Pulsar
Geminga
PSR 1055-52
RADIO
RADIO
RADIO
RADIO
No Known Pulse
RADIO
OPTICAL
OPTICAL
No Known Pulse
OPTICAL
OPTICAL
No Known Pulse
OPTICAL
No Known Pulse
X-RAY
GAMMA RAY
INTENSITY AS A FUNCTION OF TIME
0 .5 1.0
PERIOD ~ 33 mSEC
PERIOD ~ 150 mSEC
PERIOD ~ 89 mSEC
PERIOD ~ 237 mSEC
PERIOD ~ 197 mSEC
TIME IN FRACTIONS OF A PULSE PERIOD

- however total electromagnetic small: $L_{em} << \dot{E}$

e.g. Crab: $L_X + L_\gamma \sim 0.1\dot{E}$, $L_{radio} \sim 10^{-8}\dot{E}$

("by-product" of pulsar's main activity)

2. Crab nebula

a) Main emission:

Bulk of $\dot{E}$ emitted as a relativistic magnetized wind.

The pulsar wind visible when interacts with external matter.

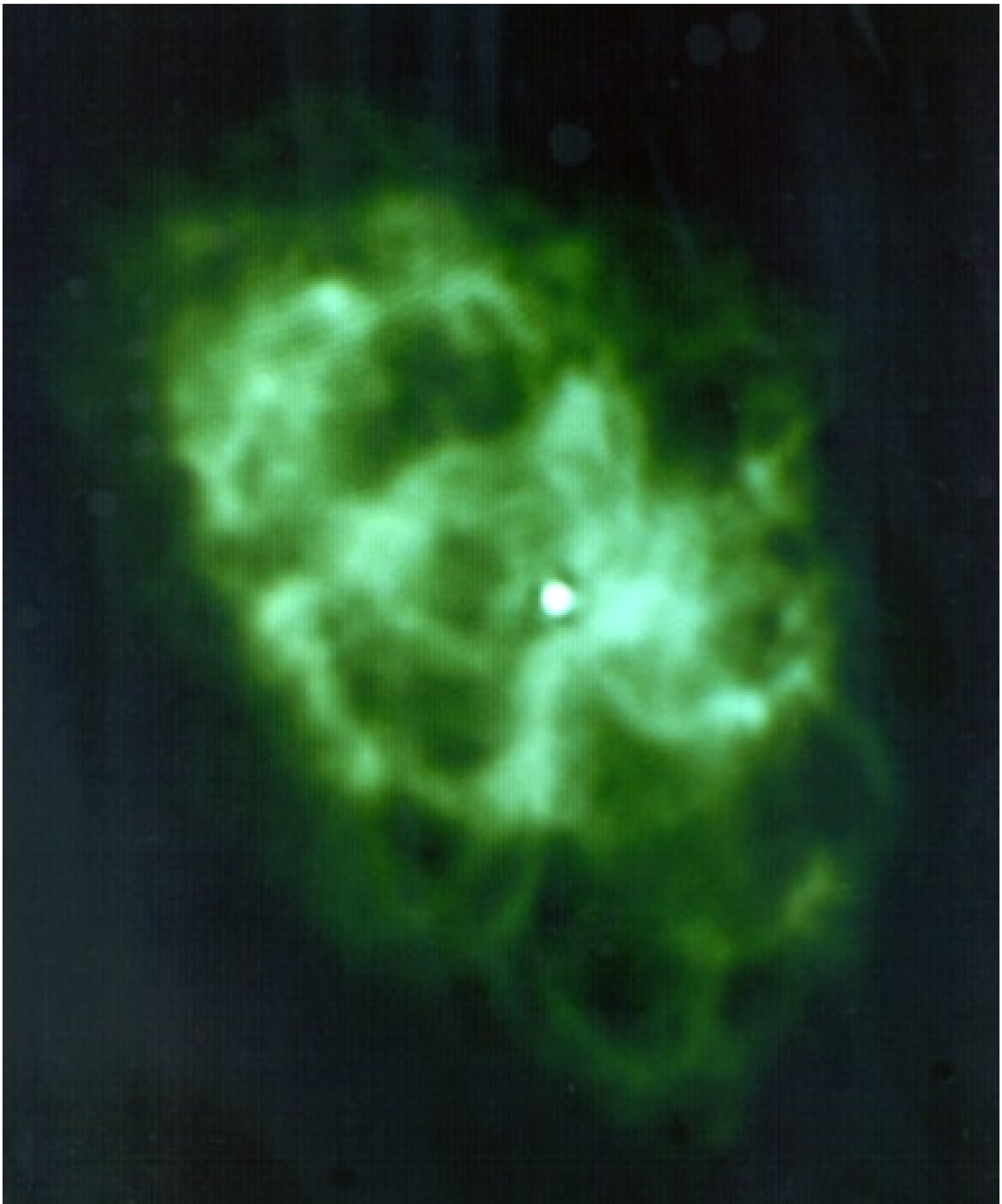
b) Pulsar wind nebulae

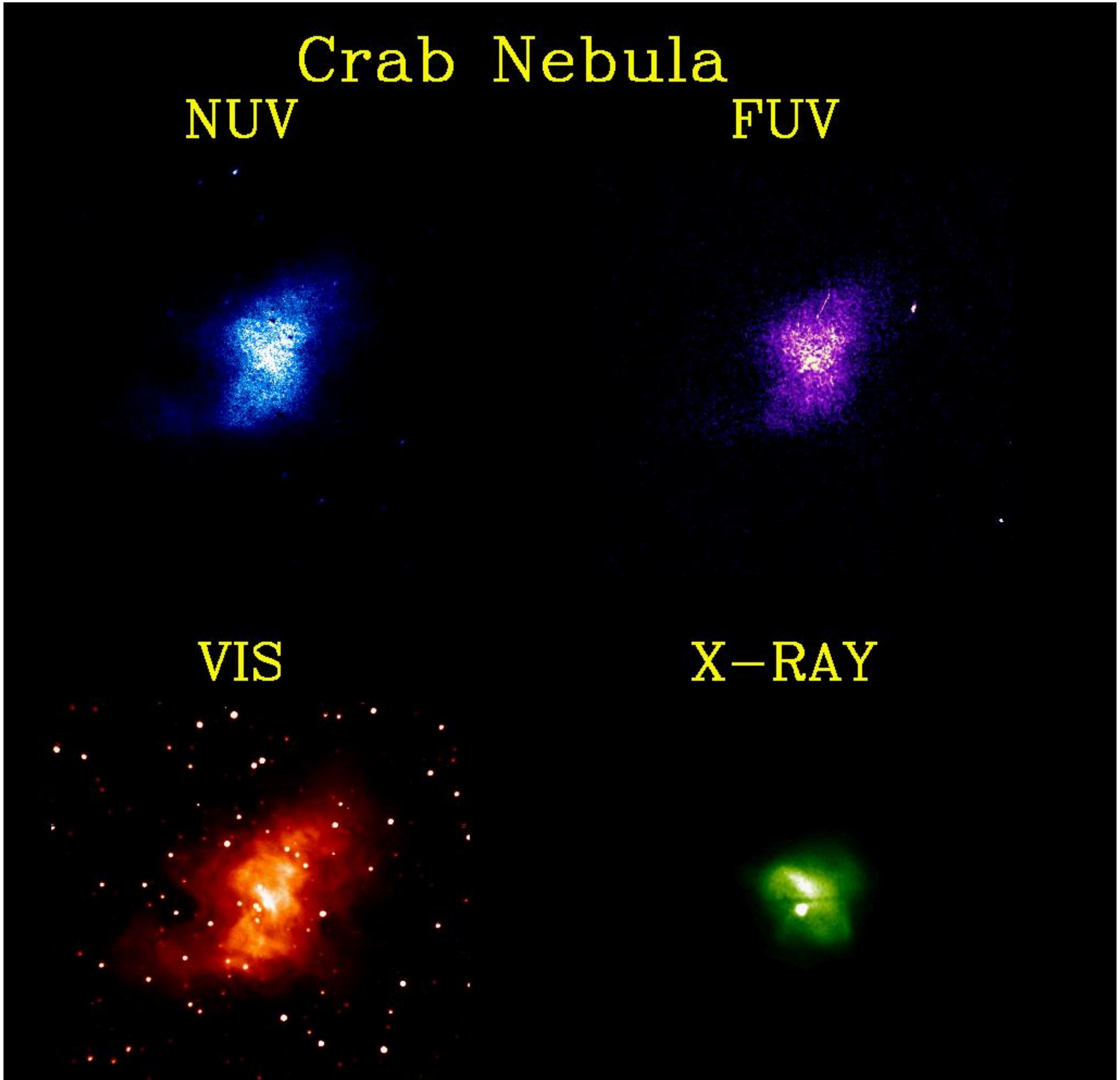
- very young pulsars (~ 1000 years) still in SNR:

pulsar wind confined by external pressure

- Crab Nebula - a prototype (SN 1054):

expanding bubble, seen radio, optical and X-ray nebula




Crab Nebula
NUV
FUV
VIS
X-RAY

- Synchrotron radiation by relativistic electrons (positrons) from the central pulsar

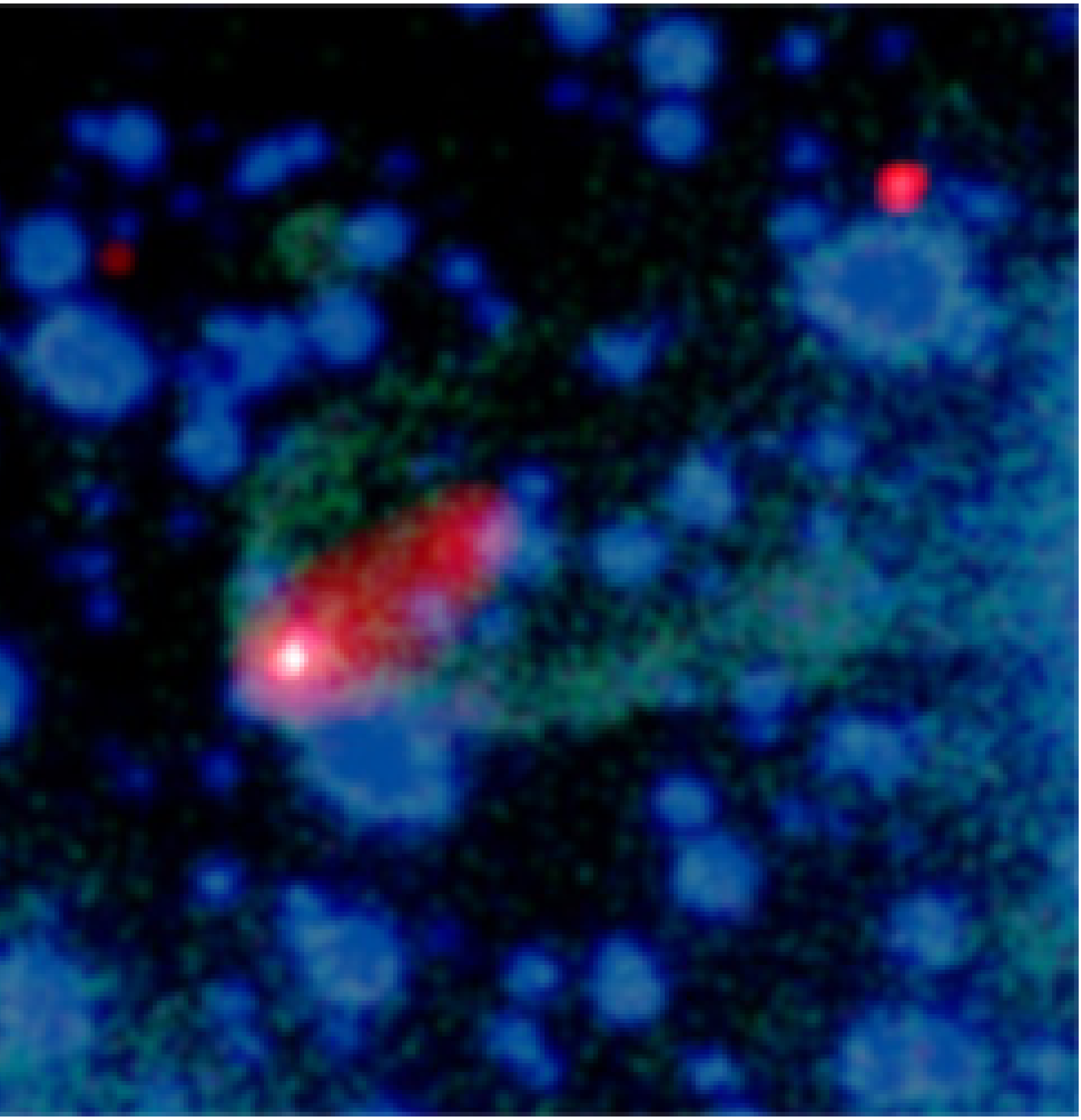
- radio emission - traces "integrated history" (long electron lifetime)

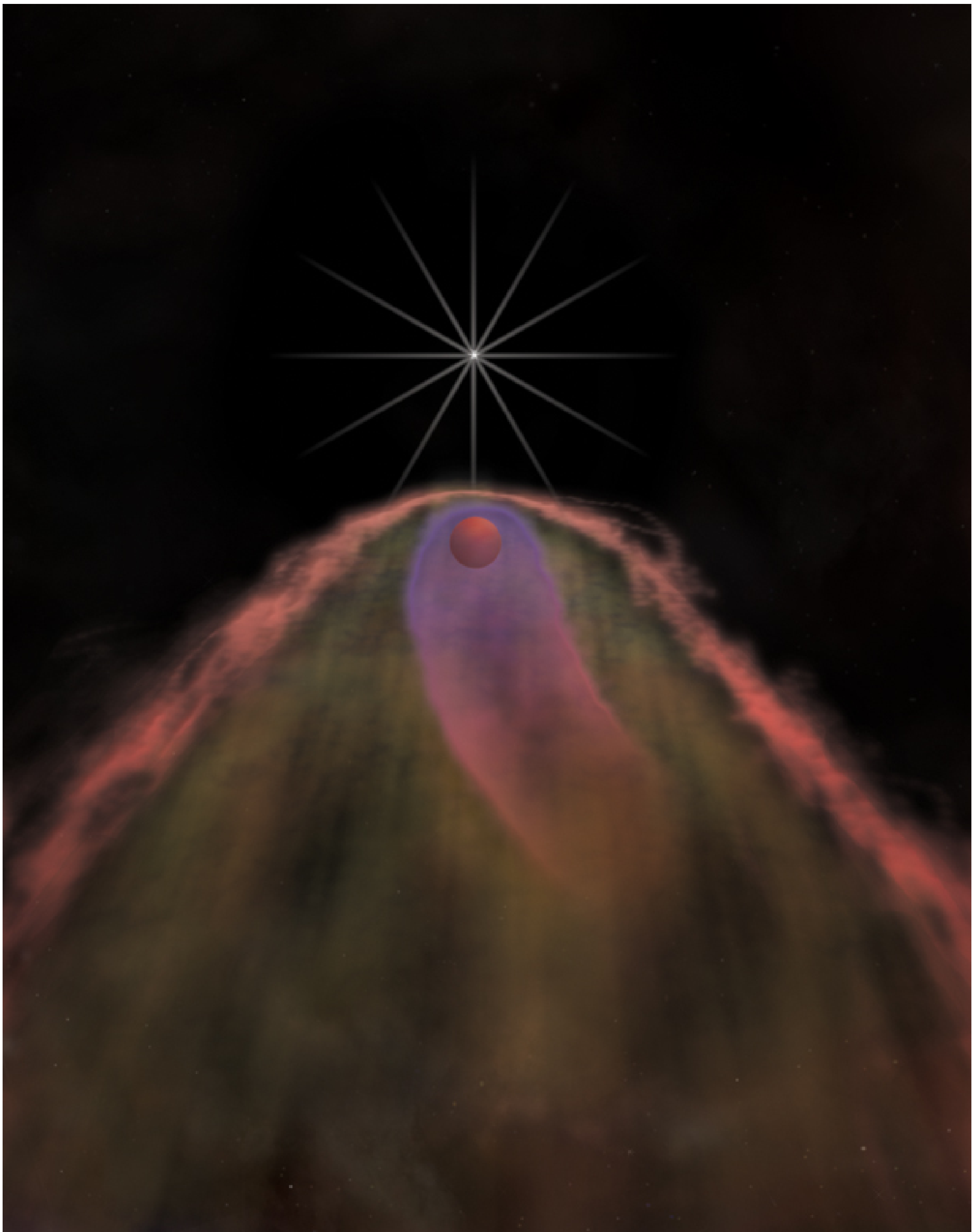
- X-ray emission - current pulsar state (short lifetime)

c) Bow-shock nebulae

Older pulsars: SNR dissipated, neutron stars move at $\sim \mathbf{500 km s^{-1}}$.

Pulsar's wind generates a bow shock.





d) Properties of the Crab Nebula

- wind terminated by shock at $r_s = 0.1pc$
- wind energy

$$\dot{E} = W_{Poynting} + W_{kinetic}$$

- model of Kennel and Coroniti (1984): very good fit of spectrum with $\gamma_{wind} = 3 \times 10^6$ and

$$\sigma = \frac{W_{Poynting}}{W_{kinetic}} = 0.003$$

before the shock.

- the wind at $r_s = 0.1pc$ is dominated by kinetic energy of plazma with $\gamma \sim 10^6$

3. Pulsar wind models

a) Basic idea:

- rotating magnetized neutron star generates electromagnetic radiation (Pacini 1967, Gold 1968)
- strong electric field is induced, $\mathbf{E} = c^{-1}\boldsymbol{\Omega} \times \mathbf{r} \times \mathbf{B}$, which injects charged particles, e^+e^- pairs, into magnetosphere (Goldreich and Julian 1969; Strurrock 1970)
- electromagnetic field accelerates the plazma converting its energy into kinetic energy of the outflowing plazma (Poynting flux acceleration)

b) Historical model

Gunn and Ostriker (1969) (not realistic):

- magnetic dipole rotating with frequency $\Omega \rightarrow$
- electromagnetic monochromatic spherical waves of low frequency $\Omega \rightarrow$
- (test) particles tightly coupled to the wave by its strong magnetic field, coupling $\sim eB(mc\Omega)^{-1} > 10^8 \rightarrow$
- particles "ride the wave" at essentially constant phase;
- very effective acceleration up to the energy

$$E_c = mc^2 [\frac{3}{\sqrt{2}} \frac{eB_0}{mc\Omega} ln \frac{r_c}{r_0}]^{\frac{2}{3}}$$

- Crab: $r_0 = c\Omega = 1576 km$ (light cylinder),

$r_c = r_s = 0.1pc$

- protons: $E_c = 1.6 \times 10^{15} eV \approx 1.6 \times 10^{6} m_p c^2$

unfortunately, pulsars do not radiate strong electromagnetic waves of rotation frequency Ω

c) Current (most promising) model

- observations hints: mechanism needed to effectively convert $\dot{E}_{rot}$ into kinetic energy of the wind, employing magnetic field, with $\sigma >> 1$ near the light cylinder and $\sigma << 1$ at $r \sim 0.1pc$.

-the problem of pulsar emission, especially converting the Poynting flux into kinetic energy of the outfowing matter, turned out to be very complex and difficult (e.g. Michel 2001)

Recent results

- Contopoulos, Kazanas and Fendt (1999) first self-consistent solution of the axisymmetric magnetosphere of an aligned rotating magnetic dipole (MHD)
- split-monopole-like open field lines far from the light cylinder, $r sin\theta >> R_{lc}$
- field lines velocity

$$\mathbf{v}_E = c\frac{\mathbf{E}\times\mathbf{B}}{B^2} = c(\hat{r}\frac{x^2}{1+x^2} + \hat{\phi}\frac{x}{1+x^2})$$

$$x \equiv \frac{r sin\theta}{R_{lc}}$$

$$\gamma_E = (1-(\frac{v_E}{c})^2)^{-\frac{1}{2}} \rightarrow \frac{r sin\theta}{R_{lc}}$$

for $r sin\theta >> R_{lc}$:

- the wind Lorentz factor becomes $\gamma_{wind} \rightarrow \gamma_E$

- particles "surf-ride" on the electromagnetic field (B-parallel velocity negligible)

- the wind is a linear accelarator, $\mathbf{v}_E \sim \hat{\boldsymbol{r}}$; radiation losses negligible

4. Neutron stars with ultra-strong magnetic fields

a) Maximum energy of particles (from possible potential difference)

$$E_{max} = 3 \times 10^{22} \frac{\mu}{10^{33} cgs} \left(\frac{\Omega}{10^{4} s^{-1}}\right)^2 eV$$

- neutron star magnetic moment $\mu > 10^{32} cgs$ for $B > 10^{14} G$:

$B = 10^{12} G, P = 0.033 s, E_{max} = 6 \times 10^{18} eV$

Maximum energy $\sim 10^{21} eV$

only for ultra-strong magnetic fields, $B \sim 10^{14} G$

and fast rotation $(\boldsymbol{\Omega = 10^4 s^{-1}, P = 0.63ms})$

Most promising sources: fast rotating neutron stars with ultra-strong magnetic fields

b) High-field neutron stars

- Magnetars in Soft Gamma Repeters (4 known): $\boldsymbol{B \sim 10^{14} G}$, periods now $\sim \boldsymbol{5 - 10s}$; probably born with short periods $\sim$ 1ms
- Anomalous X-ray Pulsars (AXP) similar B and P as magnetars (possibly the same class of neutron stars), 6 known (and candidates)

- Radio pulsars with magnetar field (recent discovery in Parkes Pulsar Survey) magnetic field $\boldsymbol{B = 10^{14} G}$ and periods P=3s,6s.