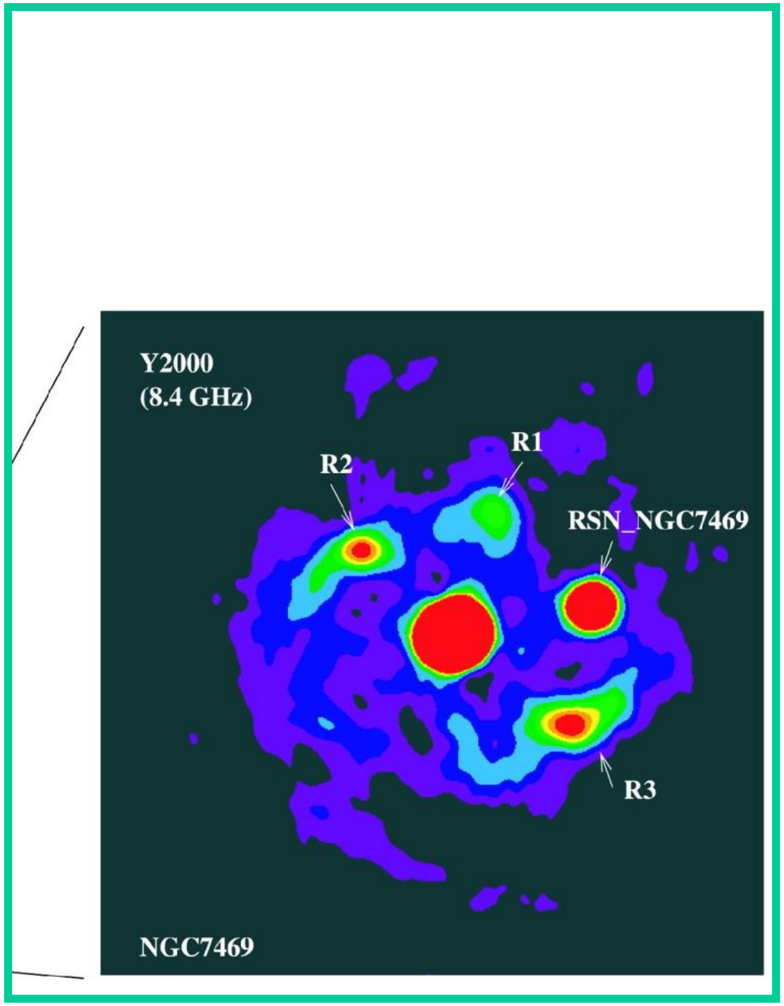
Supernovae



Supernova SN1994D, in the galaxy NGC 4526 (type S0), observed with HST

Historical Supernovae:

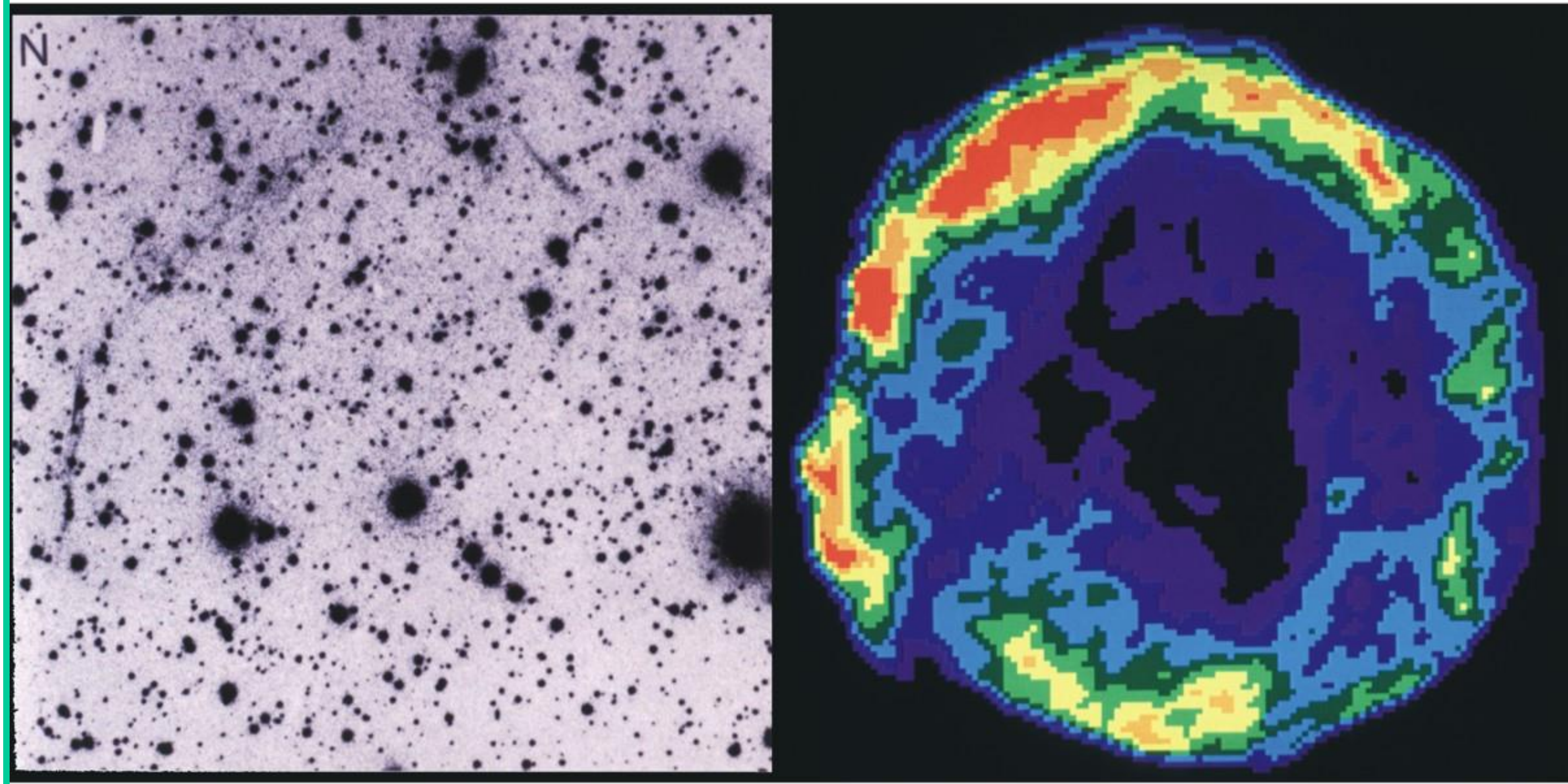
9 in ~2000 yr

~1/200 yr

Name	Year	Type	Age	Opt.	SNR
	(185)		~1800	*	(V)
	(386)		~1600		(V?)
	(393)		~1600		(V?)
Lupus	1006	I?	995	*	V
Crab	1054	II	946	*	V
3C58	1181	II	819	*	(V)
Tycho	1572	Ia	428	*	V
Keplero	1604	I	396	*	V
Cass-A	1670?	II?	330?	*	V

Optical/Radio

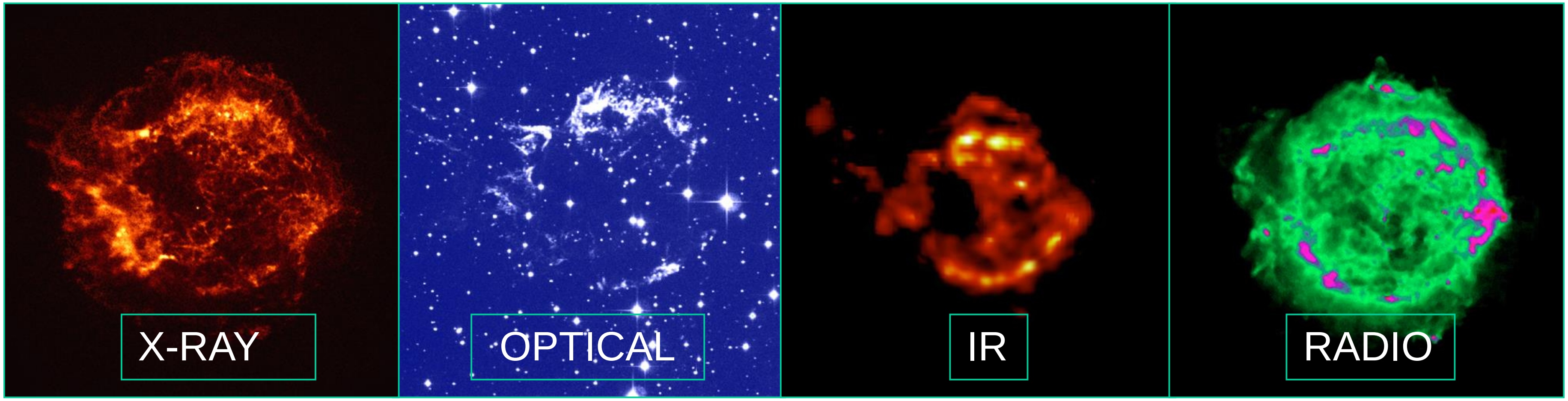
3C 10 - TYCHO'S SUPERNOVA REMNANT



Palomar Observatory - 200 inch Telescope
Optical Image (Red Light)

NRAO - Very Large Array
Radio Image (1370 MHz)

RSN at different frequencies



Cas A (1667 or 1680)

OPTICAL CLASSIFICATION

Type I (Ia, Ib, Ic):

Light max lasts ~1 week, then exponential decrease (~3mag. in ~25 days)

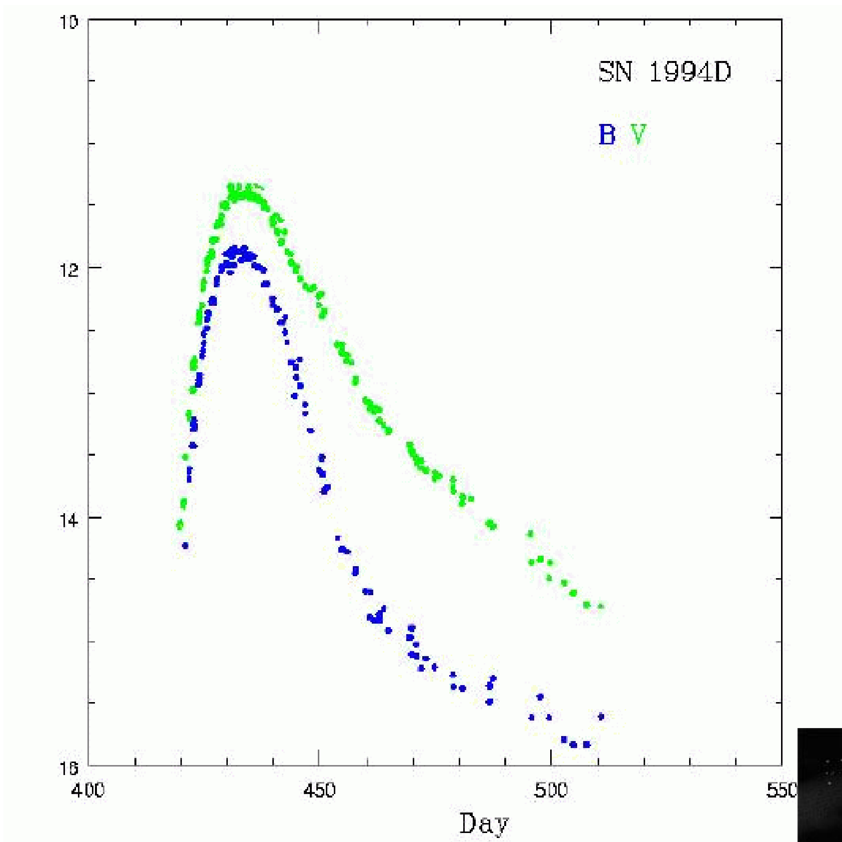
Type II:

Less homogeneous class (linear decrease / presence of a plateau)

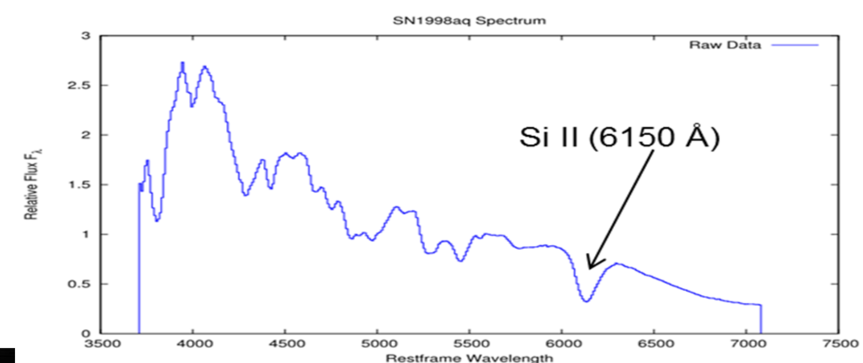
OPTICAL CLASSIFICATION (1)

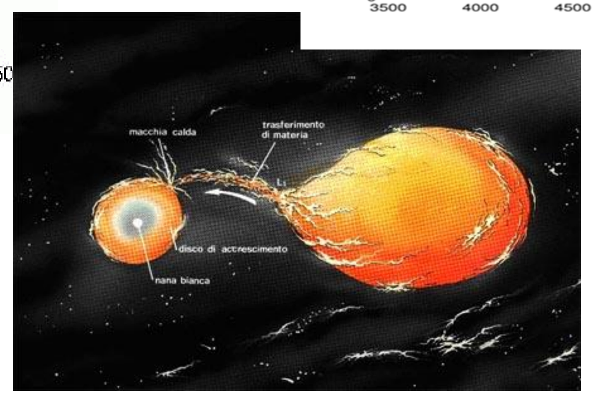
TYPE Ia (in all morphological class of galaxies)

- Strong absorption SiII line
- Associated with old stellar population
- Progenitor star: white dwarf; accretion of matter onto a companion in a binary system. Exceeded the Chandrasekhar's limit a nucleosynthesis process begins.



Light curve of SN 1994D

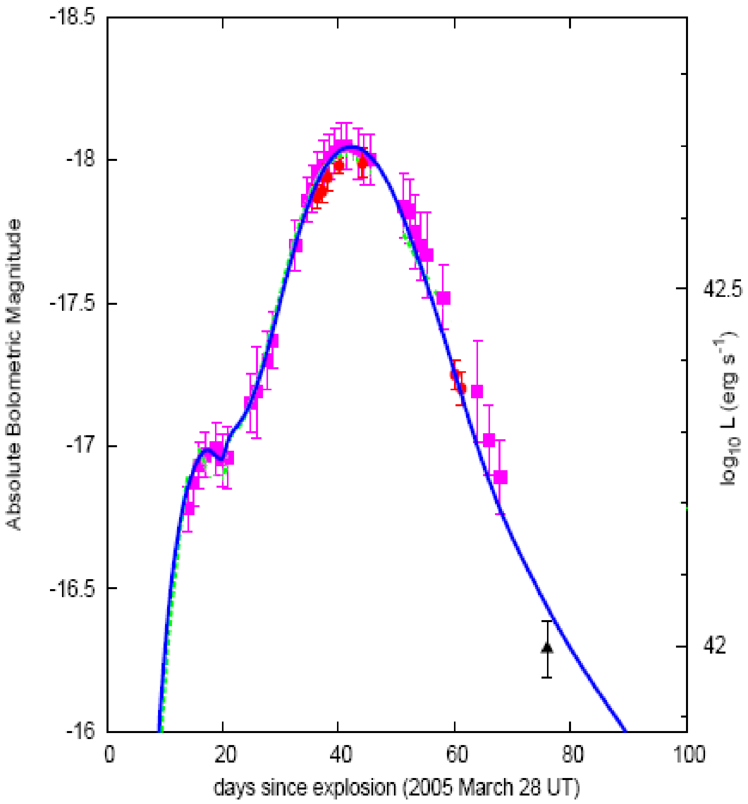




Spectrum of SN1998aq (type a), after one day from the luminosity max (in band B) a strong absorption line is present. It is due to ionized Si.

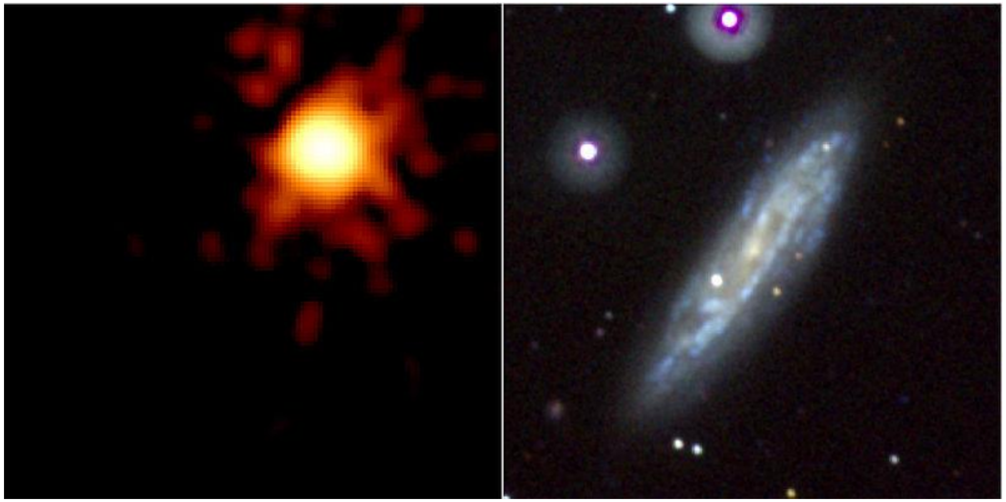
OPTICAL CLASSIFICATION (2)

TYPE Ib – Ic (in spirals)



Light curve of SN 2005BF

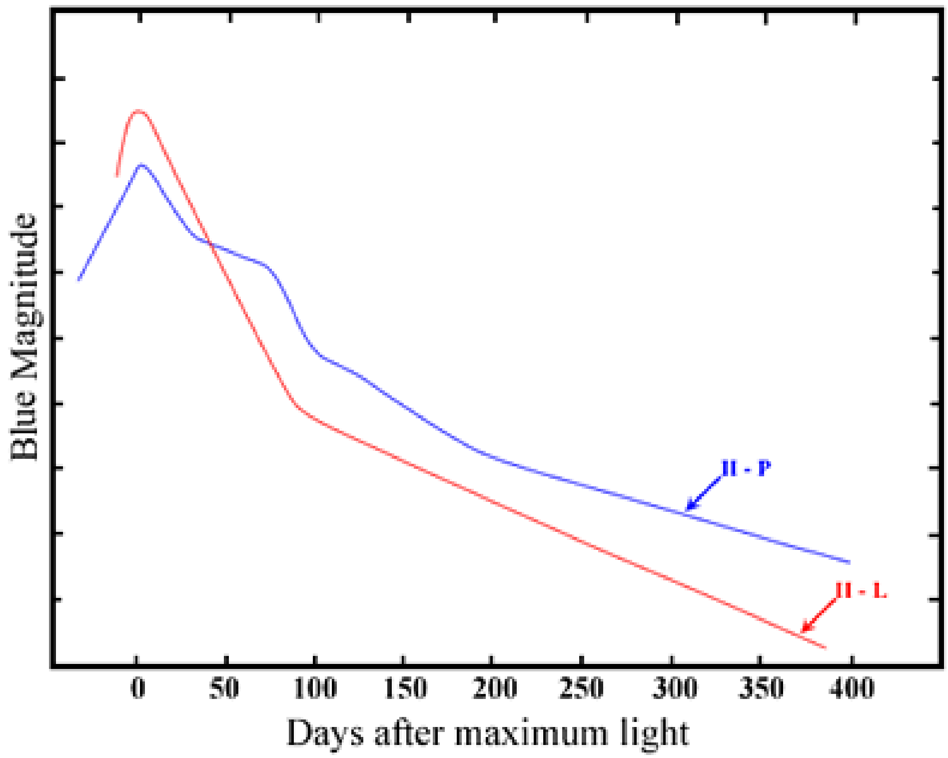
- No H lines
- Ib: He lines
- Ic: no He lines
- Associated with younger stellar population
- Progenitor star: more massive, redder and evolved star (Wolf-Rayet)
- Less bright than Ia



Supernova 2008D (type Ib) in the galaxy NGC 2770, in X-ray (left) and in optical (right).

OPTICAL CLASSIFICATION (3)

TYPE II (L-P) (in spirals)



- H lines
- Associated with young and metal rich stars (I population)
- Progenitor star: red giant or massive star
- Linear or Plateau non differences in spectroscopy

SN 1987A (type II-P) in the Large Magellanic Cloud

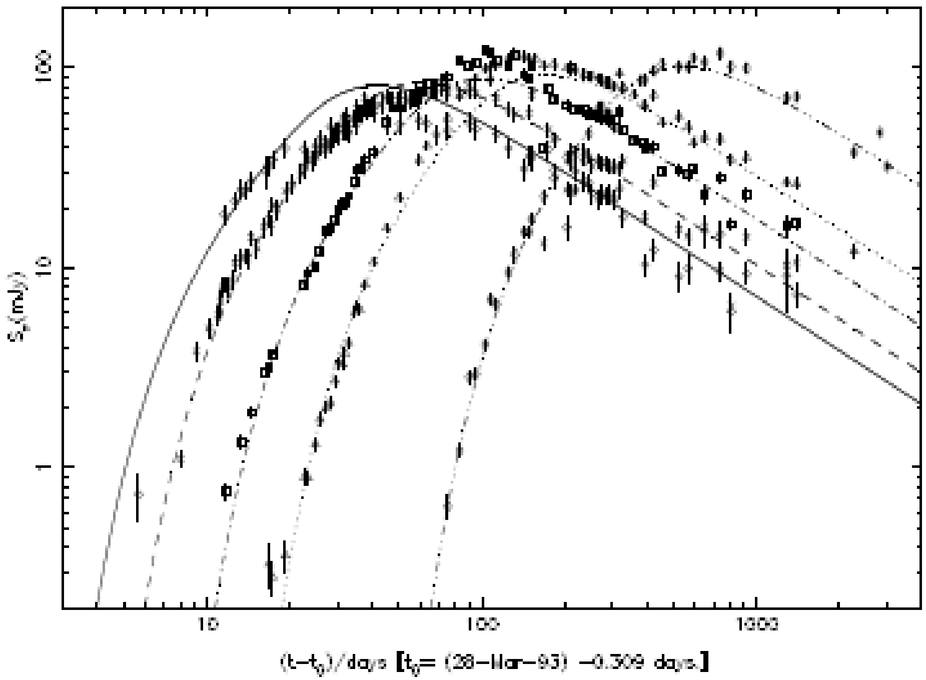
Properties of SN

TYPE I		TYPE II
$\leq 1M_{sol}$	**Ejected Mass**	$\geq 1M_{sol}$
$\geq 10^4 km/s$	**Velocity of the ejected mass**	$\leq 10^4 km/s$
$\approx 10^{50} - 10^{51} erg$	**Kinetic Energy**	$\approx 10^{50} - 10^{51} erg$

Radio observations

Type Ia: **No radio emission** $S \leq 0.1 mJy$

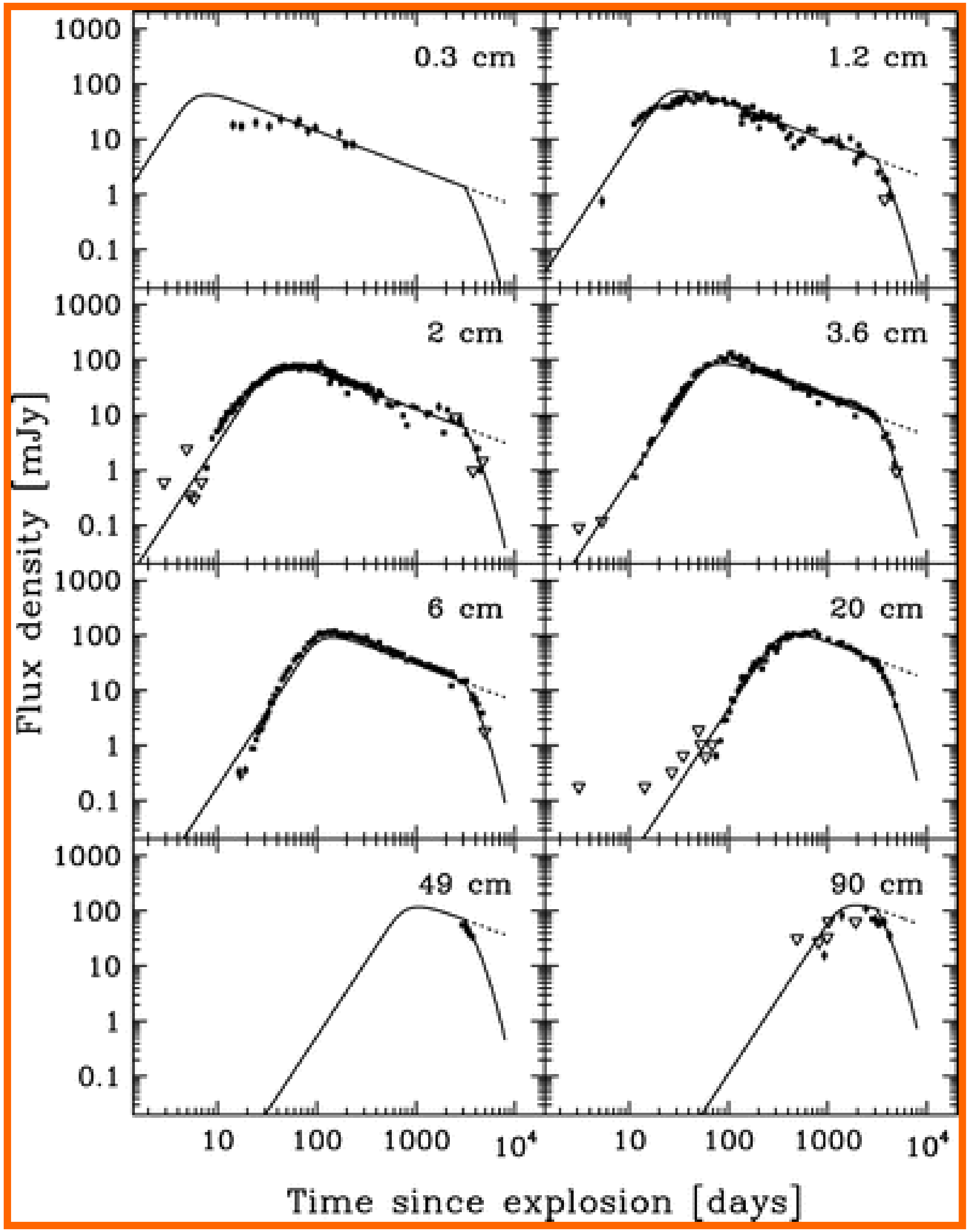
Type Ib/c: **Radio emission**
Steep radio spectrum $S \propto \nu^{\alpha}, \alpha \leq -1$



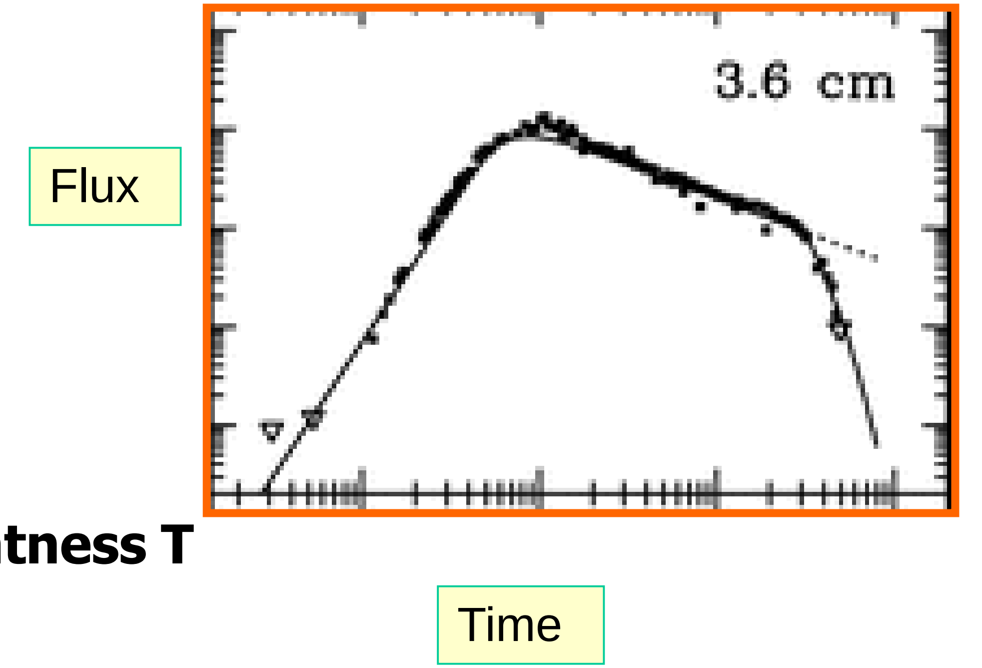
Type II: **Radio emission with large range of luminosities**
Flatter radio spectrum

$S \propto \nu^{\alpha}, \alpha \geq -1$

Radio light curve at different frequencies



Light curves of other SNRs in Panagia+, 2007 AIP Conference vol. 924



All SN have common properties:

-Synchrotron emission with high brightness T

-Absorption decrease with time; the emission appears at high frequencies then, with a time delay, at lower frequencies

-At each frequency in the graphic flux density (S) versus time: S

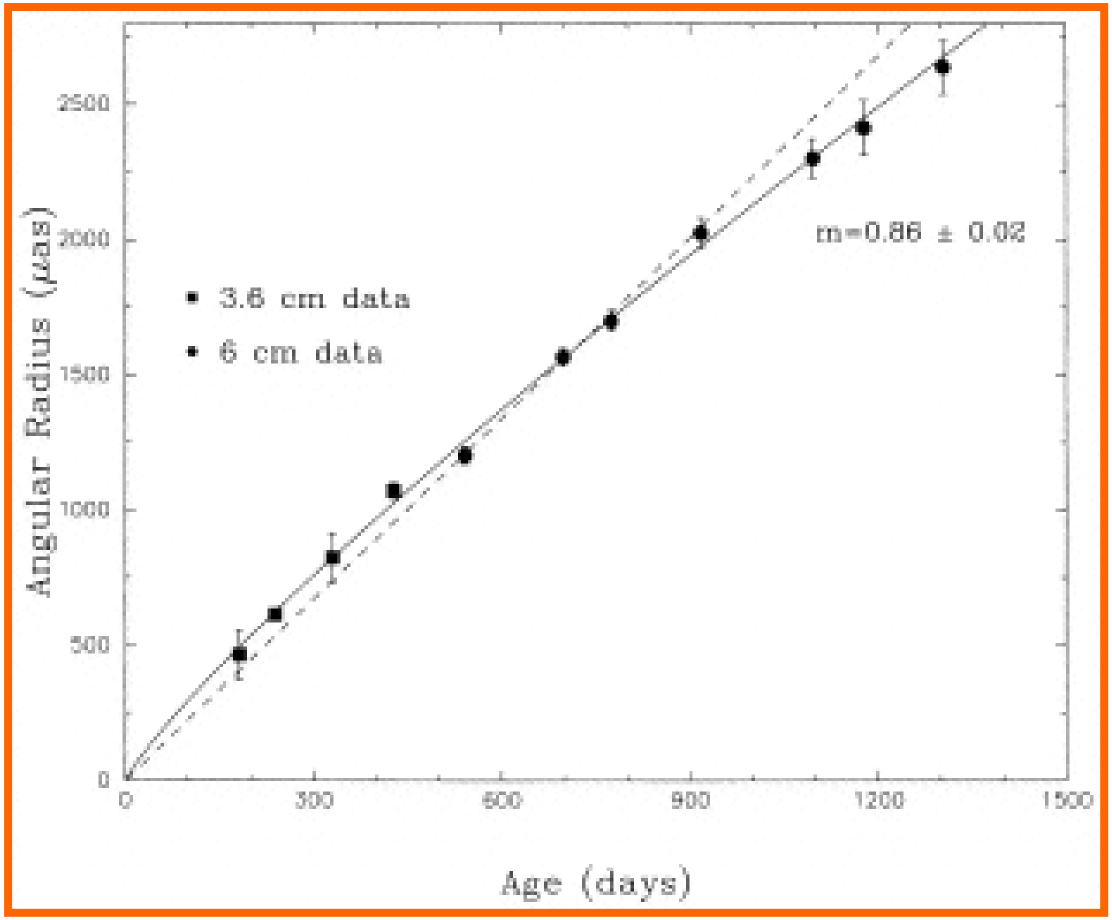
1) reaches the maximum (optical depth ~1)

2) decreases with a power law

3) asintotic negative value of the spectral index (non-thermal, optical thin)

Deceleration of shock wave expansion

SN1993J in M81



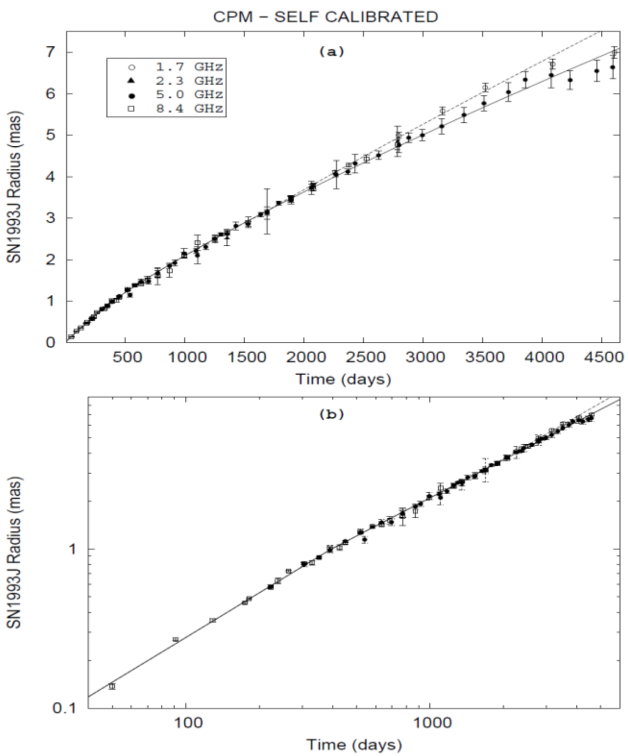
Gradual deceleration with velocity ~15000 km/s

Angular radius of SN 1993J vs. days after explosion. The continuous line results from a fit of $R \propto t^m$ (t = time after explosion) to all the data. The value of m obtained is 0.86 ± 0.02. For comparison, we show a straight-line fit (m = 1) to all the data as a dashed line (Marcaide+ 1997).

Deceleration of shock wave expansion

SN1993J in M81

Marti-Vidal et al. 2010, who presented "Radio emission of SN1993J: the complete picture. I. Re-analysis of all the available VLBI data."



	5 to 22 GHz			1.7 GHz
	m_1	m_2	t_{br} (days)	m_3
CPM selfcal[a]	0.933 ± 0.010	0.796 ± 0.005	390 ± 30	0.87 ± 0.02
CPM ph-ref[b]	0.933 ± 0.010	0.795 ± 0.005	390 ± 40	0.83 ± 0.02
Model fitting[c]	0.94 ± 0.06	0.798 ± 0.007	270 ± 70	0.90 ± 0.03
Bartel 1[d]	0.93 ± 0.02	0.798 ± 0.006	390 ± 50	0.84 ± 0.06
Bartel 2[e]	0.82 ± 0.03	0.796 ± 0.016	1000 ± 700	0.84 ± 0.06
Marcaide[f]	0.845 ± 0.005	0.788 ± 0.015	1500 ± 300	0.87 ± 0.03

[a] Using CPM-measured supernova sizes from images obtained from self-calibrated visibilities, as described in Marcaide et al. (2009).
[b] Using CPM-measured sizes from images obtained from phase-referenced visibilities.
[c] Using model fitting to the visibilities.
[d] Using the shell sizes reported in Bartel et al. (2002).
[e] Using the sizes reported in Bartel et al. (2002), but taking only the epochs later than day 182 after explosion (i.e., the day of the first epoch reported in Marcaide et al. 2009).
[f] Refit using the shell sizes reported in Marcaide et al. (2009).

Equation 1

$$R(t) = \begin{cases} r_{\rm br}\ (t/t_{\rm br})^{m_1}\ , & t < t_{\rm br} \\ r_{\rm br}\ (t/t_{\rm br})^{m_2}\ , & t \geq t_{\rm br}. \end{cases}$$

Equation 2

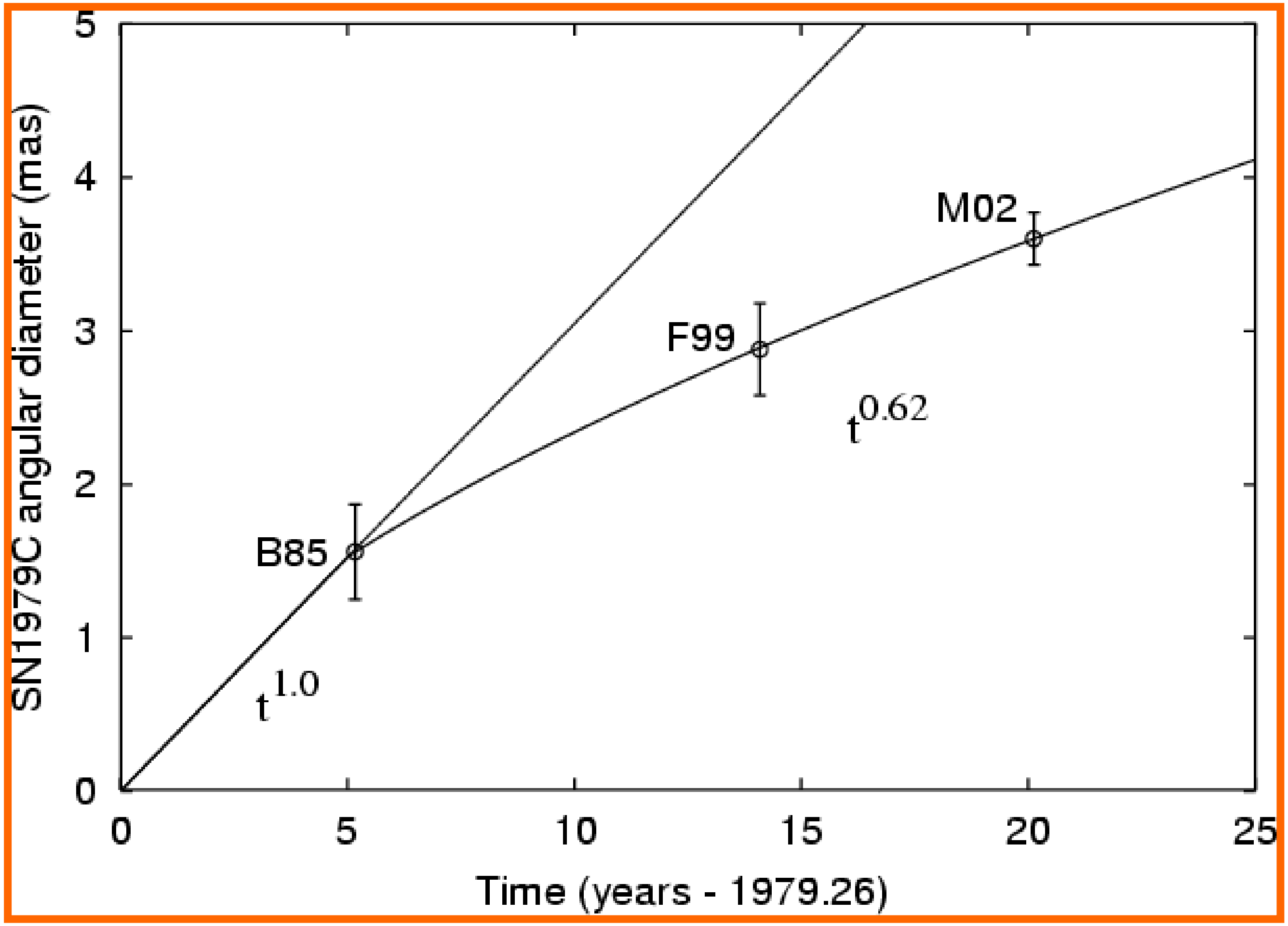
$$R(t) \propto t^{m_3}$$

Expansion of SN1993J. Dashed line corresponds to the fit with equation 2 using the data at 1.7 GHz, the solid line to the fit with equation 1 using all the data. **(b)** as **(a)**,but in logarithmic scale.

Deceleration of shock wave expansion

Supernova in free expansion for the first ~6 anni the strong deceleration

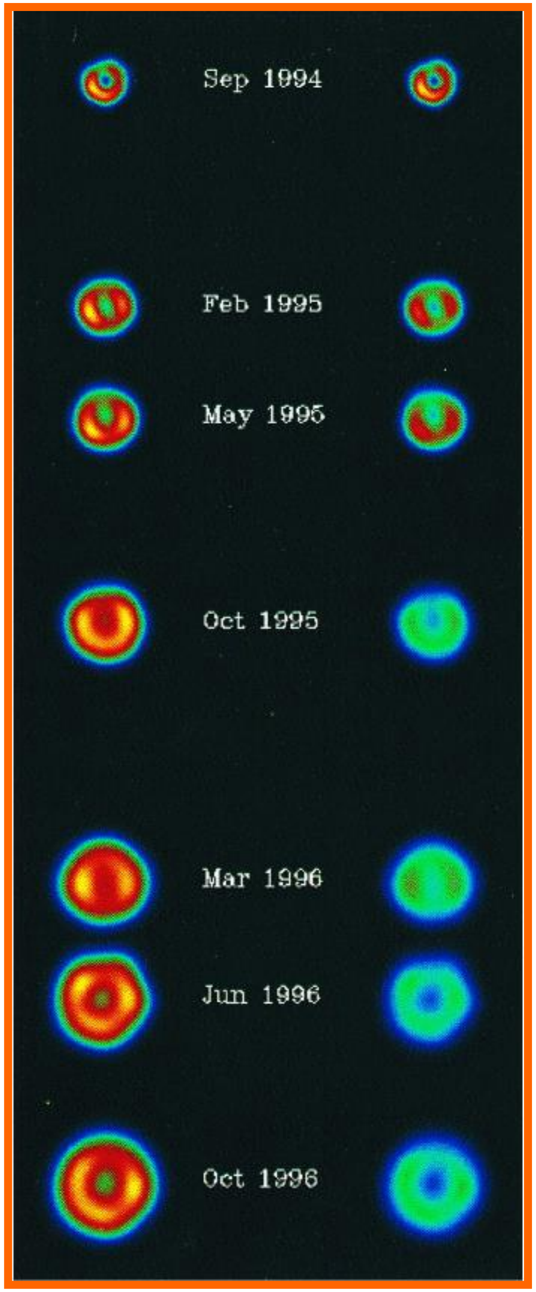
Hypothesis: the shock wave travelled in the thin medium of the bubble created by the progenitor star then the shock front entered a high-density region of the circumstellar medium.



SN1979C (M100) type II L : the angular dimensions have been observed with VLBI by many authors in different years (1985, 1999, 2002) Marcaide+ 2002

SN 1993J in M81 a 6cm
(Marcaide+1997)

Radio structure constant except a scale factor dependong on the time; good agreement with the Chevalier model

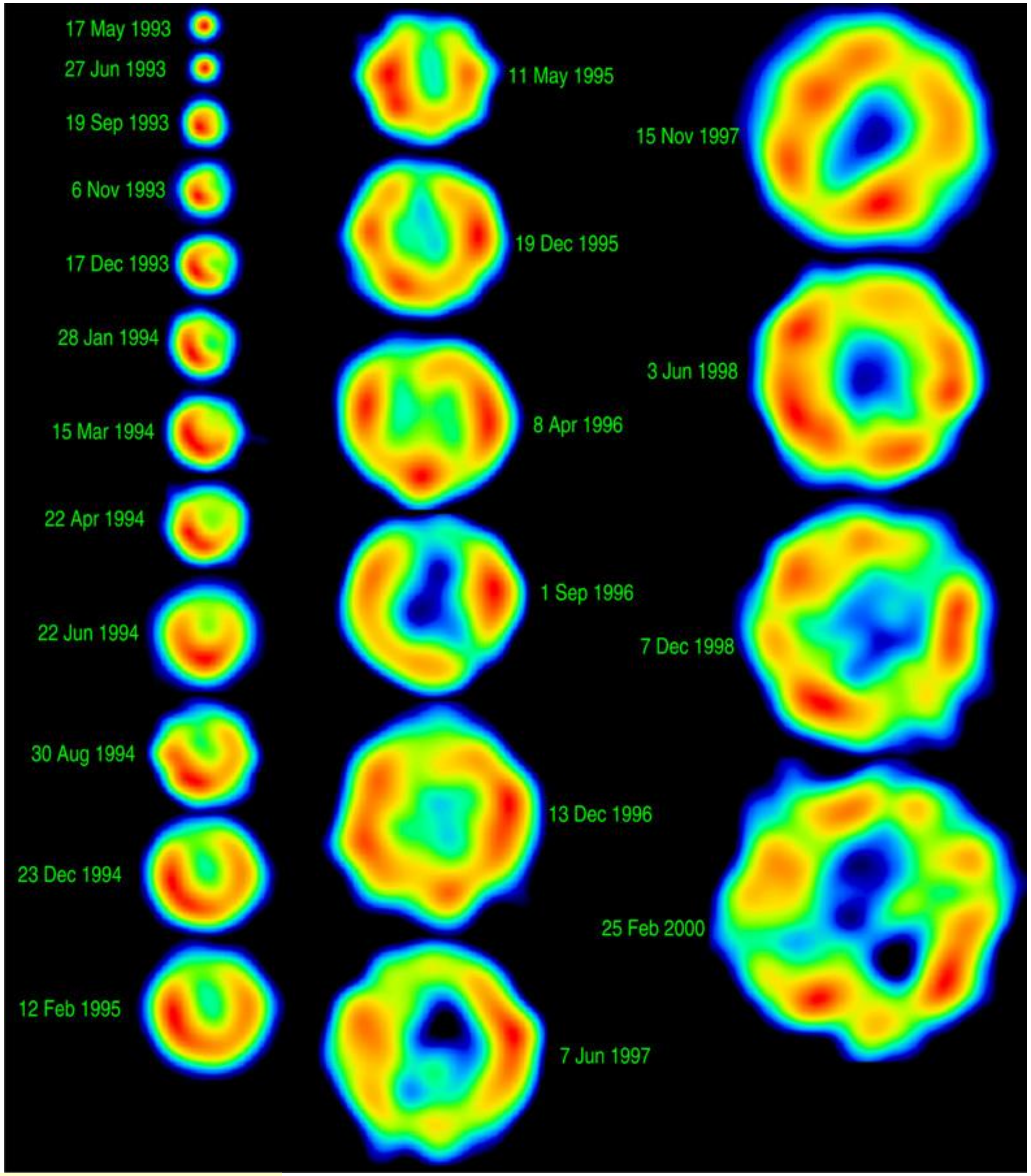


SNR 1987A

In the Large Magellanic Cloud observed for more than 20 years with the Compact Array (Australia) at 8GHz

A burst of neutrinos was retrospectively detected by Kamiokande II. This event was interpreted as due to the collapse of the core of a type II SN.

The SNR is increasing the brightness, probably due to the interaction with the circumstellar medium, pre-existing to the SN.

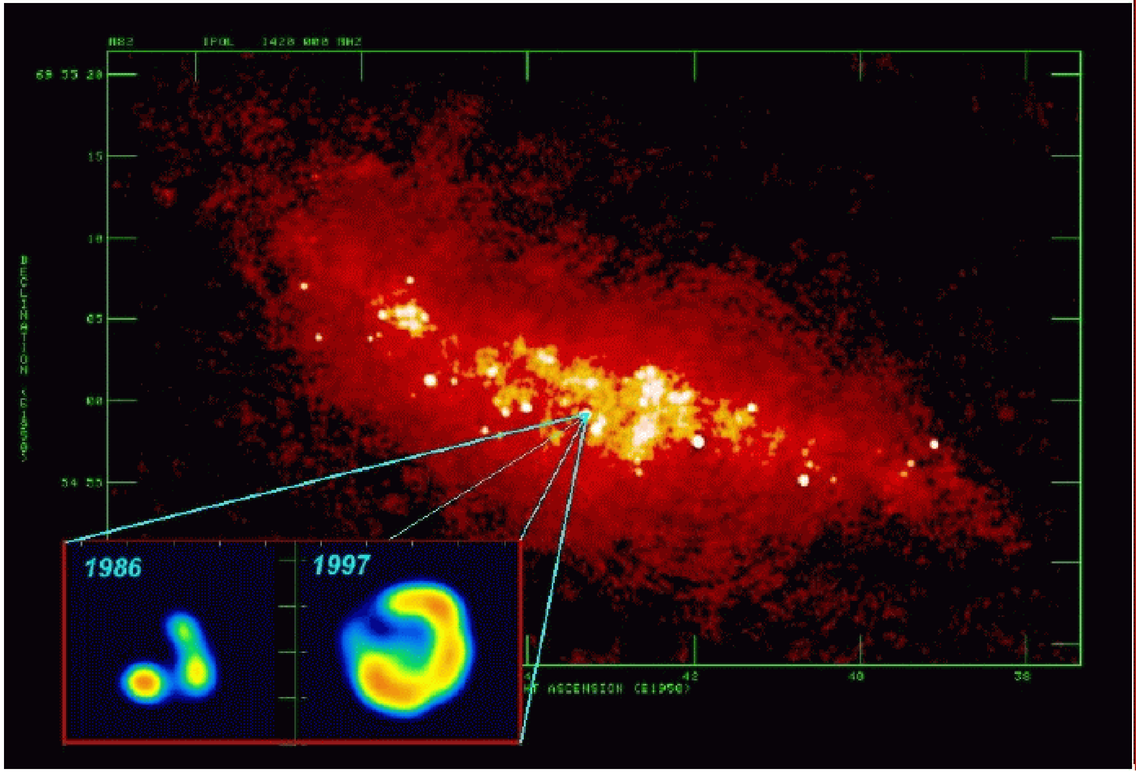


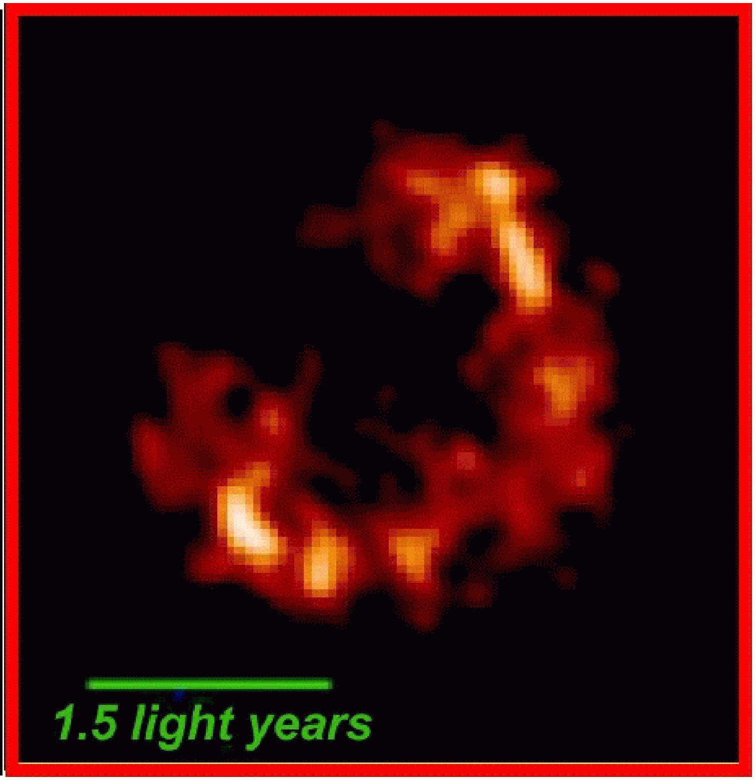
The brightest SNR in the last 400 years

M 82

- Comparison between 1992 and 2004 data (9.75 year timeline): measure of the expansion velocities for 10 compact objects.

velocity range between 2200 and 10500 km/s





VLBI *Observations*

Information about the interaction between the eject material and the circumstellar medium, that is usually due to the wind of the progenitor star of the SN.

Es. SN1993J Bartel+2002

SN1986J Bietenholz+2002

Emission Model (Chevalier 1982, 1998)

- **The radio emission is associated with the interaction region between the supernova ejecta and the wind lost from the progenitor star prior to the explosion.**

- **The circumstellar medium is ionized and warmed by UV-Xray flashes of the first phase.**

-

- **The rapid increase of the flux density is due to the decrease of absorption processes. In fact the emission region expands and the absorption processes (both internal and along the l.o.s) decrease.**

Processes due to free-free absorption and synchrotron self-absorption can be present.

Magnetic field

In the plerions (see 3C58, Crab Nebula) H is disordered and fills the SNR.

In the young SNR (see Tycho) H is radial , indicating that it stretched by the ejected material.

In the old SNR H is tangential, freezed with the material.

$$B \sim 10^{-4} - 10^{-5} Gauss$$

$$H_{eq} \sim 1.2x10^{-4} Gauss \qquad H_{RM} \sim 7.4x10^{-5} Gauss$$

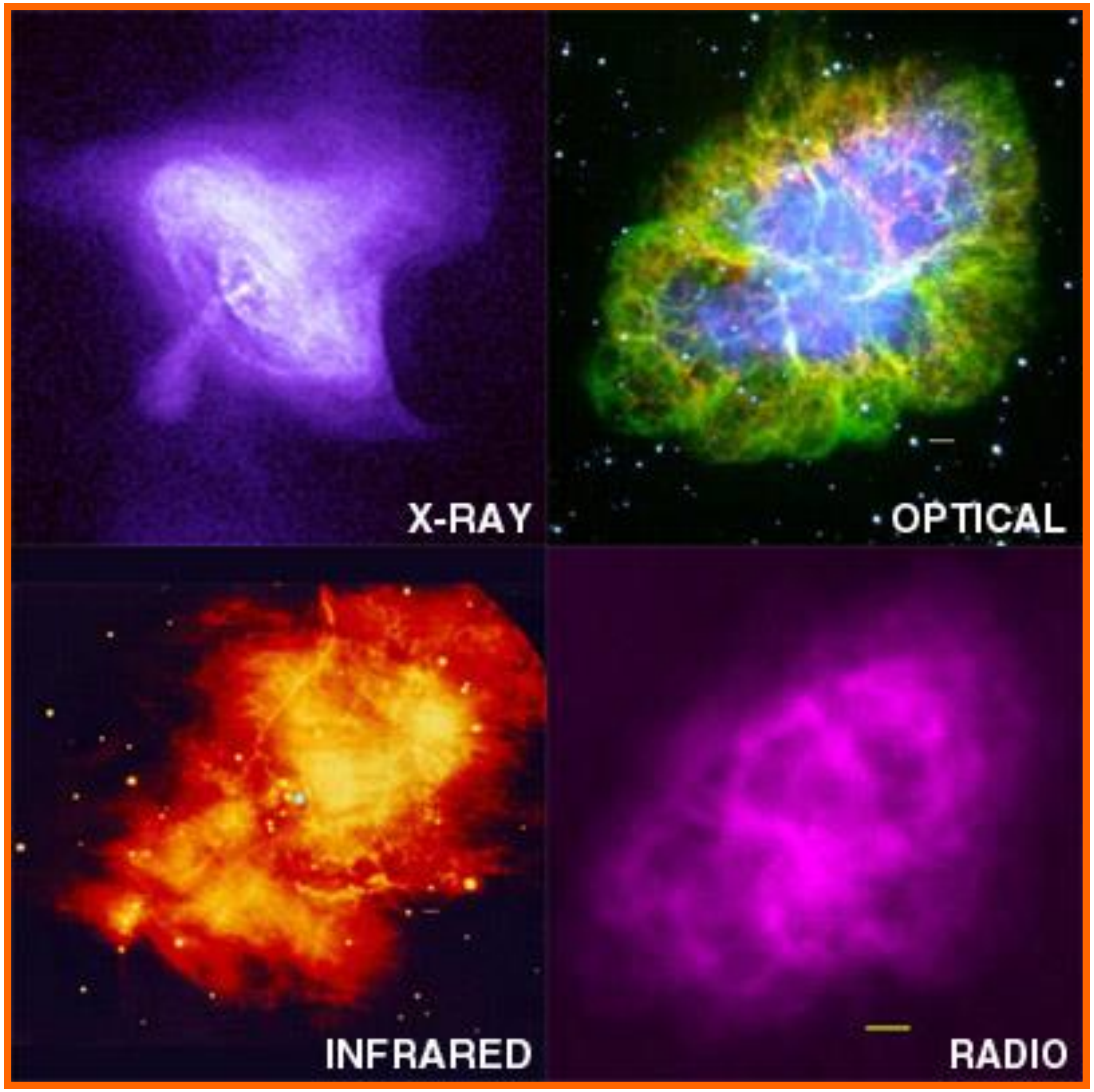
Crab Nebula

- Luminosity ~10^{38} erg/s, mostly in optical and X range (electrons that emit in X-ray must be accelerated)

- Pulsar

- Synchrotron mechanism in radio an in X

- Using kinematic computation and the present velocity v(esp)=1450 km/s it follows that the expansion must be accelerated



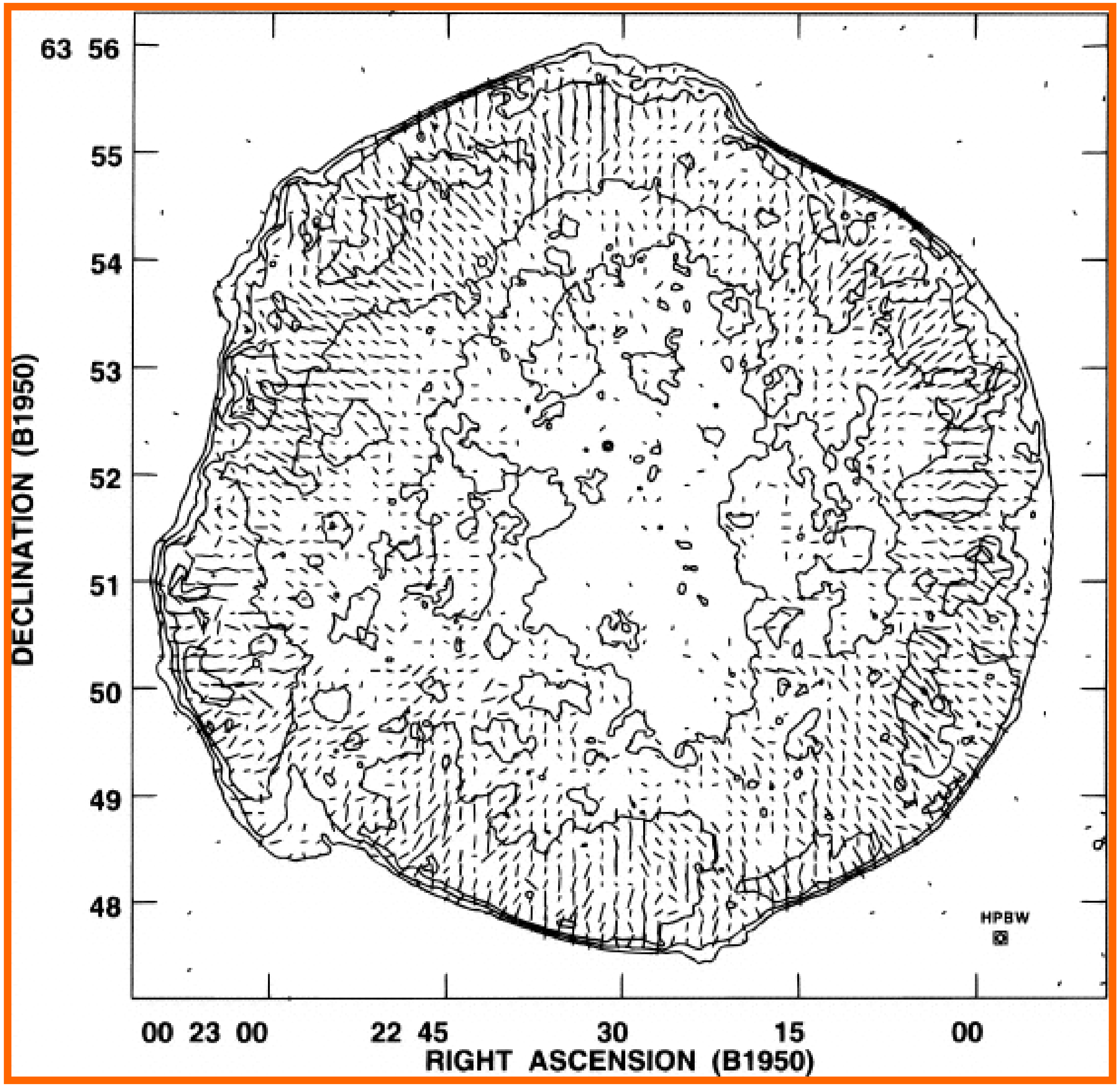
3C58 (possible SNR A.D. 1181)

At different frequencies

Magnetic Field

Vectors showing the direction of the magnetic field in Tycho's SNR (3C10) superimposed on contours representing the total intensity at 1375 MHz.

The resolution is 4 arcsec. The length of the vectors represents the polarized intensity at 1375 MHz; a length of 1 corresponds to an intensity of 100 μJy beam^{-1}. For clarity, only one in 20 vectors was plotted, so that the final spacing between points is 8 The beam size is indicated at the bottom right corner. The contours are at 0.3, 3, 6, 10, and 15 mJy beam^{-1}.



SN: dynamical evolution

Phase 1: free expansion

Explosion: a fraction of M_0 (total mass of the star) is ejected with high velocity (5-10 10^3 km/s)

$V_{esp} >> C_s$ → **Shock front**

While M_0 >> CSM mass collected in the shock front

V_{esp} = const.

The gas expands adiabatically, without energy exchange

$T_{nube} V(t)^{(\Gamma-1)}$ = const.

$$\Gamma = c_p / c_v$$

In the cloud T decreases, outside the interstellar gas warms up

SN: dynamical evolution

Phase 2: Conservation of energy – adiabatic expansion

The shock front gathers material. Conventionally the free expansion stops when M_0 = M(int), then:
t=200 yr ; R(t)=2 pc

M_0 << Mass of the interstellar medium

$$M(\text{int}) = 4/3\pi R(t)^3 \rho(\text{int}) \geq M_0$$

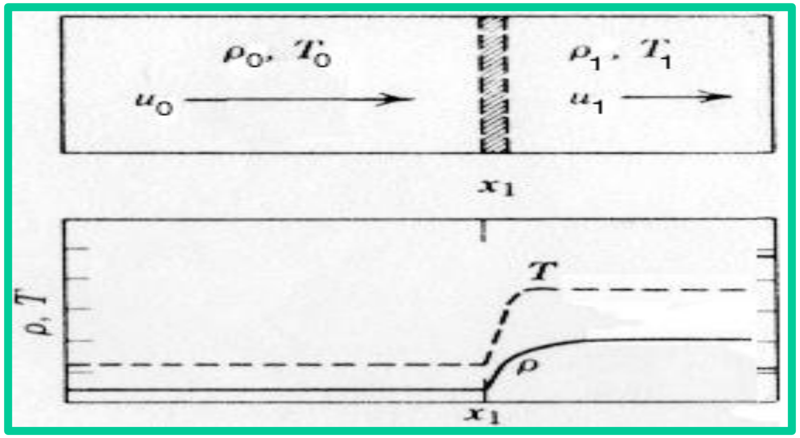
$$\rho(\text{int}) = n(\text{int}) m_H$$

Suppose that

E(tot) = kinetic energy + thermal energy

The energies are ~ equal; they conserve separately. The mass of the shock front is that of the interstellar medium:

$$1/2E(tot) = 1/2M(\text{int})v^2{}_{esp}(t)$$



Phase 2

$$= \frac{1}{2}\left(\frac{4}{3}\pi R^3(t)\right) n(\text{int}) m_H \left(\frac{dR(t)}{dt}\right)^2$$

$$R(t) = \left(\frac{75}{8\pi}\right)^{1/5} \left(\frac{E(tot)}{2n(\text{int})m_H}\right)^{1/5} t^{2/5} \cong 6x10^4 \left(\frac{E(tot)}{n(\text{int})}\right)^{1/5} t^{2/5}$$

$$v_{esp} = \left(\frac{dR(t)}{dt}\right) \cong 6x10^4 \left(\frac{E(tot)}{n(\text{int})}\right)^{1/5} \frac{2}{5} t^{-3/5} = \frac{2}{5}\frac{R(t)}{t}$$

V decreases with the collection of new material

E(tot) can be computed knowing v(esp), n(int) e t

Phase 2

In the case of a strong shock wave, immediately behind the shock, the density, the temperature and the pression are:

$$\rho = 4\rho_{\text{int}} \qquad P = \frac{3}{4}\rho_{\text{int}} v_{esp}^2 \qquad T = \frac{3}{16}\frac{m_H v_{esp}^2}{k}$$

$$T = 6.4x10^{11}\left(\frac{E(tot)}{10^{51}}\right)^{2/5} n_{\text{int}}^{-2/5} t_{anni}^{-6/5}$$

$$P = 3.5x10^{-4} n_{\text{int}}^{3/5}\left(\frac{E(tot)}{10^{51}}\right)^{2/5} t_{anni}^{-6/5}$$ **in dyne/cm²**

Phase 2

During this phase:

-Emission due to bremsstrahlung decreaes T, mainly in the X-ray interval (< 1% → negligible)

-Radiation due to recombination (C,O,N) shows lines in the optical range

These losses increase when T decreases and then

$$v_{esp} = \frac{2}{5}\frac{R(t)}{t} \qquad\qquad T = \frac{3}{16}\frac{m_H v_{esp}^2}{k}$$

v(esp) decreases → T decreases

when $T \leq 5x10^6 K$

These losses become important

Phase 2

The adiabatic approssimation is no more valid when the initial energy E(tot) become ½ . t(star) can be defined as:

$$\int_0^{t(star)} \left(\frac{dE}{dt}\right)_{CNO} dt = \frac{1}{2} E(tot)$$

$$-\left(\frac{dE}{dt}\right)_{CNO} = 8x10^{-17} \frac{n_{\text{int}}^2}{T} R^3(t)$$

$$-\left(\frac{dE}{dt}\right)_{CNO} \approx 3x10^{-4} n_{\text{int}}^{9/5} E(tot)^{1/5} t^{12/5}$$

Phase 2

It is possible to obtain:

$$t(star) \approx 13 E(tot)^{4/17} n_{\text{int}}^{-9/17} \qquad R(t(star)) = 1.7 x 10^{5} E(tot)^{5/17} n_{\text{int}}^{-7/17}$$

$$v_{esp}(t(star)) \approx 5 x 10^{3} E(tot)^{1/17} n_{\text{int}}^{2/17}$$

$E(tot) \approx 10^{50} erg$ $\quad$ $n_{\text{int}} \approx 1 atom / cm^{3}$

$t(star) \approx 2.5 x 10^{5} anni$ $\quad$ $v(t(star)) \approx 50 km / s$ $\quad$ $R(t(star)) \approx 30 pc$

$T \approx 50000 K$

Cygnus Loop, IC443

For t> t(star) the T is determined by radiation and not by expansion. The internal pressure strongly decreases.

SN: dynamical evolution

Phase 3: ISOTHERMAL CONDITION
Conservation of momentum

The increase of T due to the wave front is compensated by the cooling due to radiative losses, then T is constant when the radiative losses are ~E(tot)

Conservation of momentum not of energy

$$R^3(t) n_{\mathrm{int}} m_H v_{esp} = R^3(t) \frac{dR(t)}{dt} n_{\mathrm{int}} m_H = R^3(t(star)) \frac{dR(t(star))}{dt} n_{\mathrm{int}} m_H = const.$$

$$R(t) \propto (t + \cos t.)^{1/4} \qquad v_{esp}(t) \propto (t + \cos t.)^{-3/4}$$

$$E(t) \propto (t + \cos t.)^{-3/2}$$

SN: dynamical evolution

Phase 4: Fading out

The expansion velocity becomes comparable to the sound velocity (< 20km/s) T~10000 K, t~10^6 years from the explosion→SNR fades out

$$R(t) = \left(\frac{75}{8\pi}\right)^{1/5} \left(\frac{E(tot)}{2n(\mathrm{int})m_H}\right)^{1/5} t^{2/5} \cong 6x10^4 \left(\frac{E(tot)}{n(\mathrm{int})}\right)^{1/5} t^{2/5}$$

$$\boxed{\frac{E(tot)}{n_{\mathrm{int}}} \approx 1.6x10^{53} R^5(pc)t^{-2}(anni)}$$

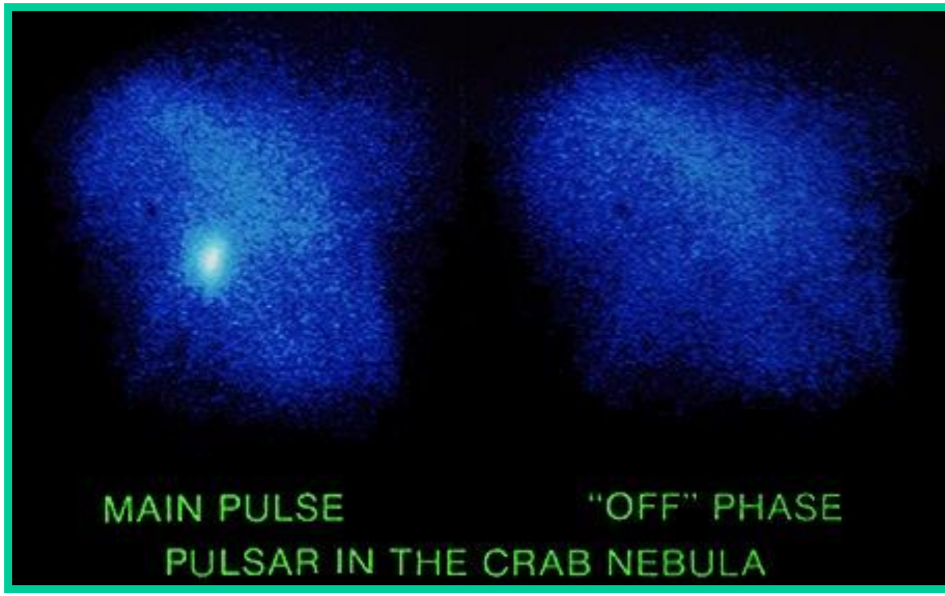
The total energy can be obtained knowing R (uncertainties of R with the fifth power). For CasA, Tycho, Keplero, Vela:

$$\boxed{E(tot) \approx 10^{50} - 10^{53} erg}$$

Limits of the model

- effects of the heterogeneous structure of the medium
- continuous replenishment of energy due the possible presence of a pulsar
- effects of the magnetic field
- presence and effects of a reflected shock

Counting the SN with diameters <30 pc we obtain a frequency of SN of 1 in 50 years (+50yr ,-25yr)



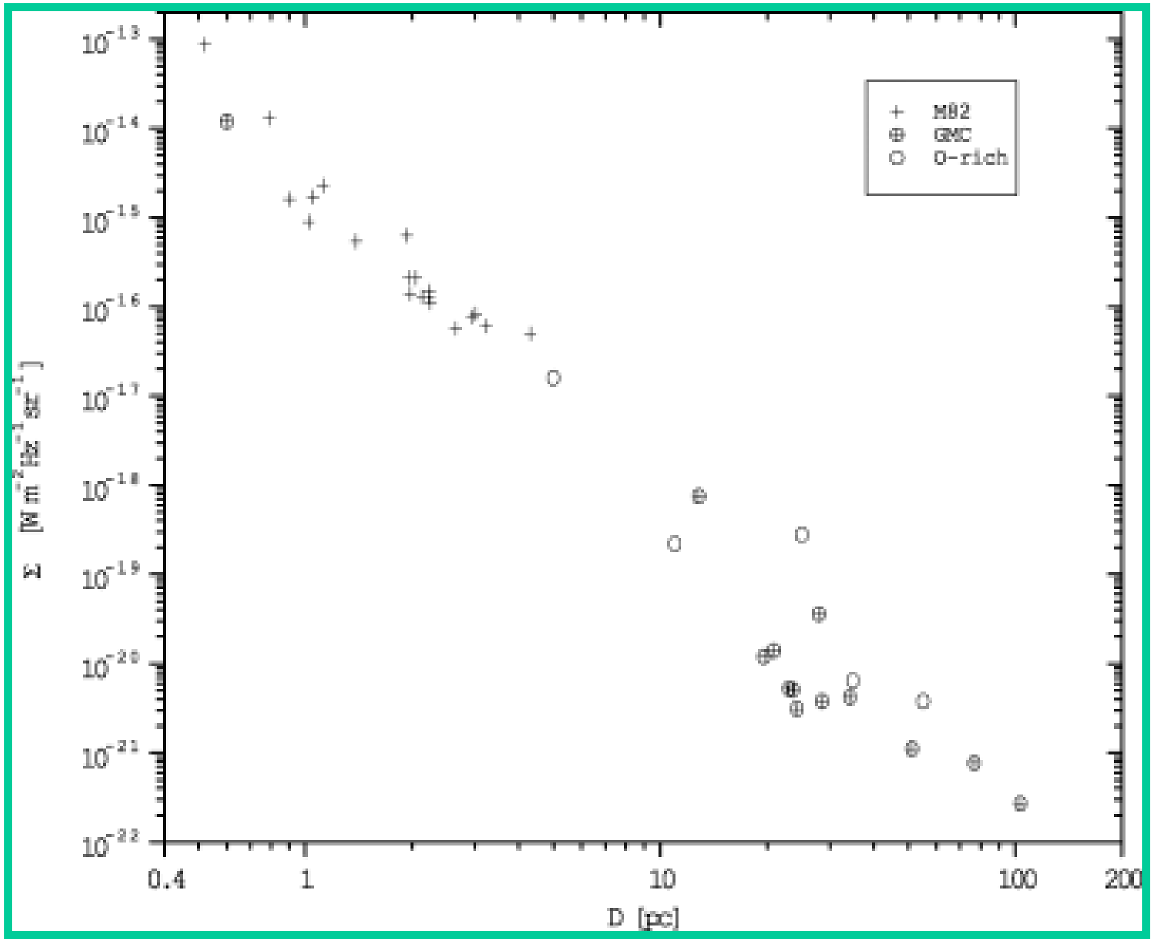
Σ -D relation

Surface Brightness – Diameter (in radio)

$$\Sigma = AD^{-\beta}$$

If we use this representaton of the data, we obtain:

β = 3.5 for compact SNR in M82, Giant Molecular Clouds e O-rich SNRs



Σ–*D* plot for M82 (crosses), GMC (encircled crosses) and O-rich SNRs (circles), Arbutina+ 2004, 2005.

Σ-D relation

In a radio source which expands adiabatically the luminosity is proportional to the diameter:

$$L \propto D^{-2\delta} = D^{-2(2\alpha+1)} \qquad B \propto L / D^2 \propto D^{-2\delta-2}$$

If the SNR can be aproximated to a shell with negligible width:

$$L \propto D^{-3\alpha-1} \qquad B \propto R^{-3(\delta+1)/2}$$

Considering an average spectral index alfa~0.5 and then delta~2:

$$\boxed{B \propto D^{-6}} \qquad \boxed{B \propto D^{-9/2}}$$

No agreement with the data

Σ -D relation

(probably non universal)

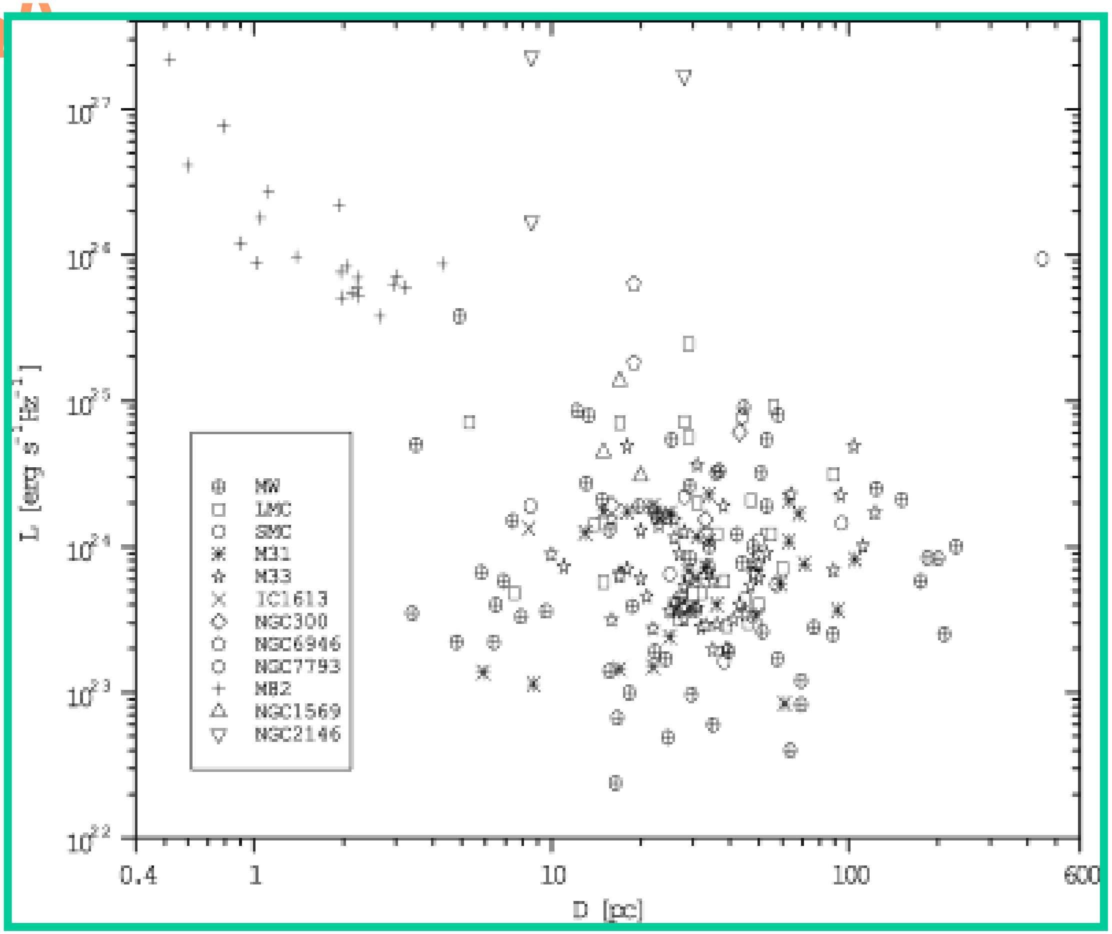
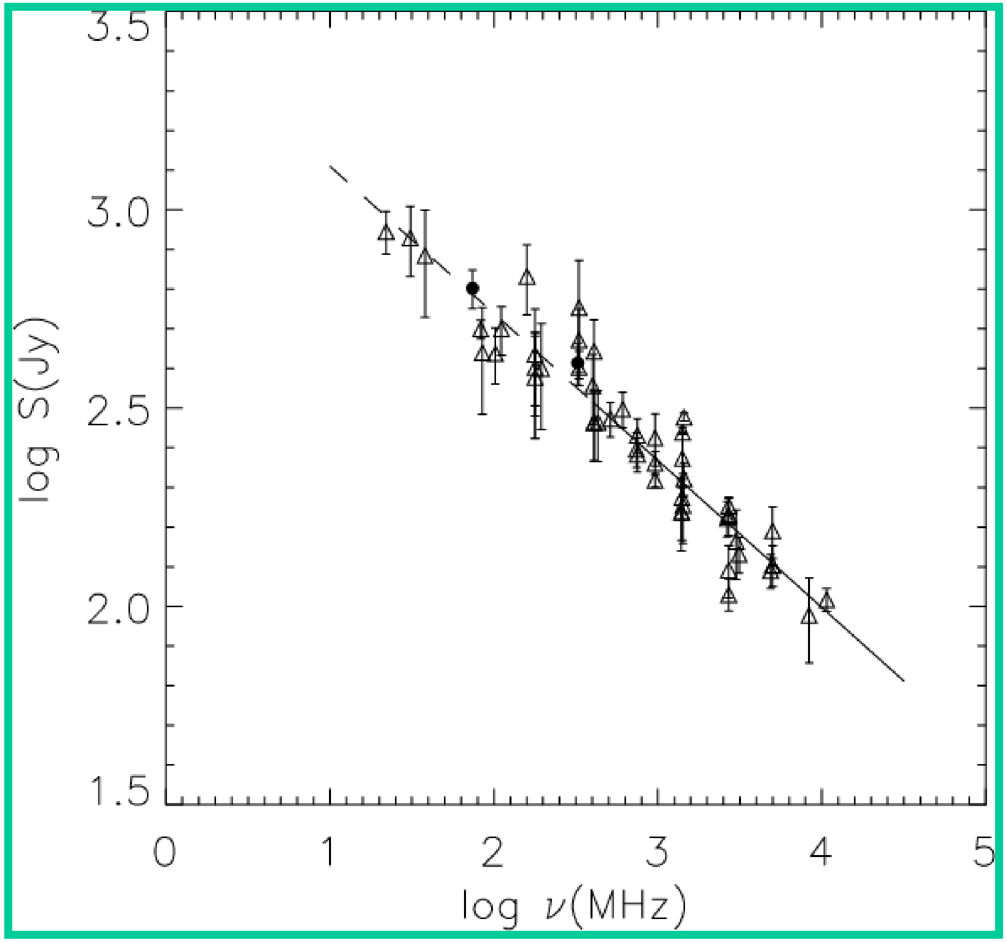


Figure shows all SNRs [including remnants of IC 1613 (1) and NGC 300 (3), 6946 (2), 7793 (2), 1569 (3) and 2146 (3)] in our sample. There is no obvious correlation between luminosity and linear diameter, except for the M82 SNRs (Arbutina+2004, 2005)

SNR W44 – Multi-frequency study

(Castelletti+ 2007)

Integrated radio continuum spectrum. The linear fit to all of the flux density values yields a spectral index alpha= -0.37+/-0.02 and is shown by the line (Baar scale of fluxes).



SNR W44 – Multi-frequency study

(Castelletti+ 2007)

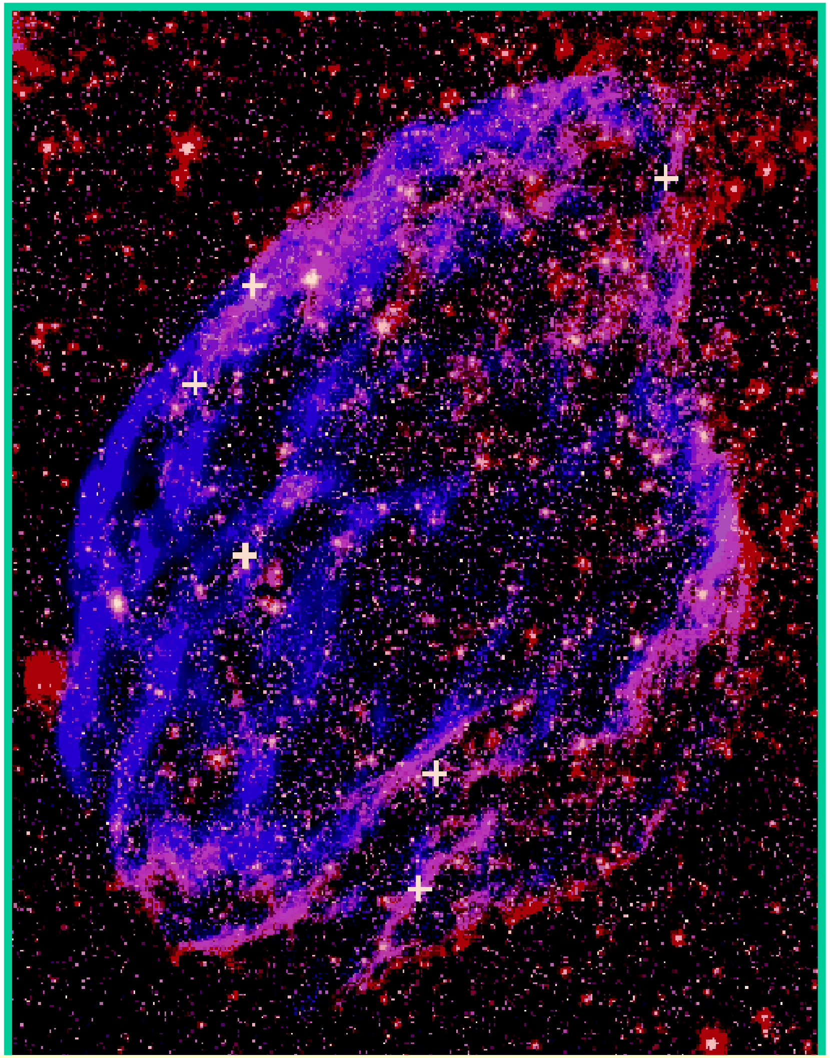
In equipartition condition and assuming isotropic radiation the total energy and the minimum magnetic field are:

$5.8x10^{49}\, erg$

$18\mu G$

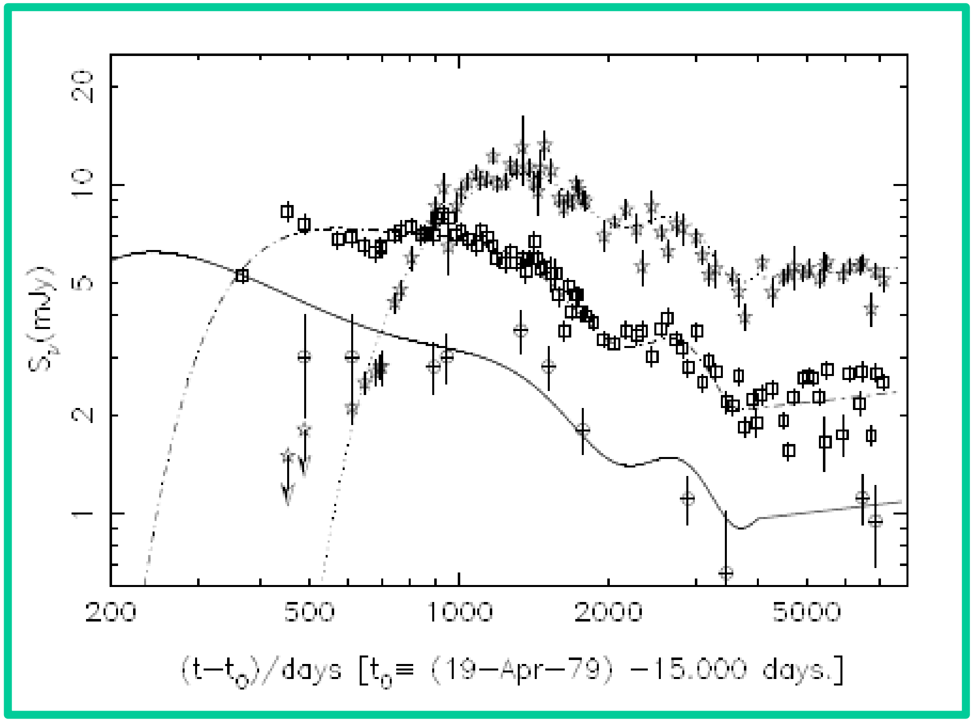
In agreement with the values obtained for other SNR with pulsar

H corresponds to the typical value of the ISM (~5microG) compressed 3-4 times



A color composite image showing the spatial correlation between the mid-infrared emission as observed by the *Spitzer Space Telescope* at 4.5micron (in orange) from Reach et al. (2006), and the new low frequency radio image at 324 MHz (in blue). Features where both spectral bands overlap are magenta in color. The positions where OH (1720 MHz) maser emission was detected are indicated with white + symbols (Hoffman et al. 2005).

RADIO OBSERVATIONS



Quasi cyclic variations:
Binary system; the companion perturbs the density of the CSM

Pulses of the preSN stellar wind are not so rapid.

Some considerations:

-The Galaxy looses through radiation of CR: $\sim 2x10^{40} erg/s$

-From equipartition in a SNR: $\sim 10^{49} erg$

-1SN in about 50 yr $\sim 6x10^{39} erg/s$ Not enough

Very old SNR, no more visible, are lacking.

In the explosion the kinetic energy is: $\sim 10^{51} erg \longrightarrow \sim 6x10^{41} erg/s$

then only 5% must be converted in energy for relativistic particles in order to satisfy the energetic request of CR.

The particles are accelerated through the Fermi mechanism (I species)

Some Gamma Ray Bursts can be due to the explosion of a massive star in a very dense medium.

Distribution of SNR in the Galaxy

-It follows the distribution of the synchrotron emission

-With respect to the height above the plane: strong concentration and then exponential decrease similar to that of the I stellar population (O,B)

Energetic considerations

The content of energy in particles and field remains almost constant, then for adiabatic expansion

$$U_{\min} \sim R^{-1}$$

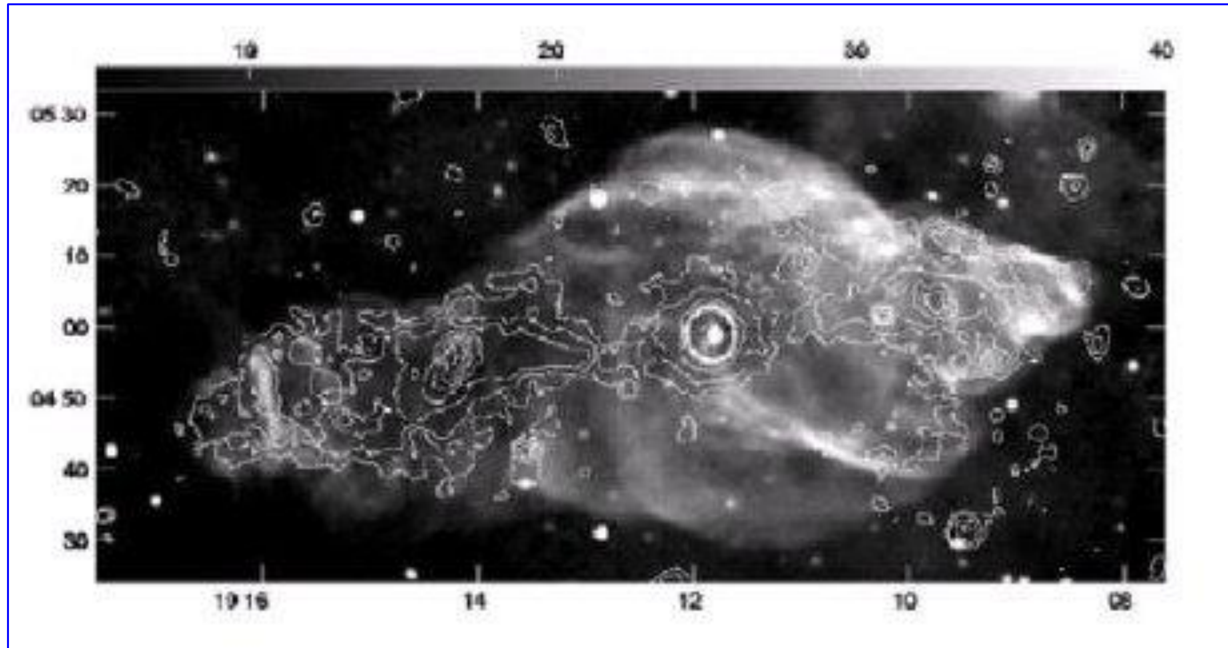
But we know that $U_{\min} \propto L^{4/7} R^{9/7}$

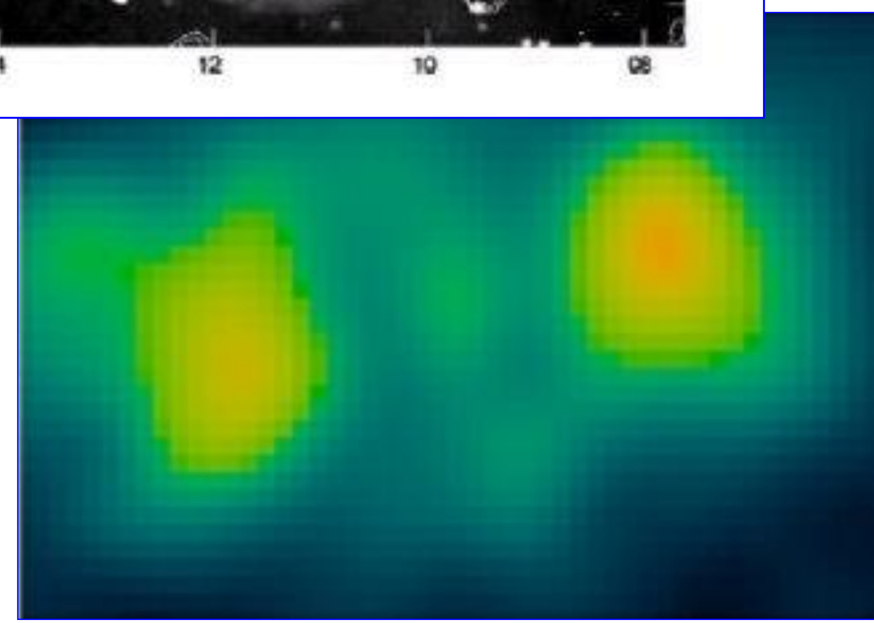
And from the luminosity-diameter relation $L \propto R^{-1.5}$

Then $U_{\min} \propto R^{3/7}$ It is necessary a riacceleration

Interaction between jet and environment

W50: Probale SNR with SS433 in the centre (map at 20 cm with 55 arcsec resolution)





- Lobes extension ~50pc

- Energy transferred to the medium

~ $2x10^{51} erg$