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Supernova Remnants as Radio Sources

One of most common, easily identifiable classes of radio sources -

Shell morphology (except ...?)

Nonthermal spectrum (i.e. if $S_\nu \propto \nu^{-\alpha}$, $\alpha \sim 0.4 - 0.7$)

Polarization

Show pictures. 5 slides (...)

Why are they like this?

Begin story with SN.

__Pre-20th Cent:__

Various ~~sixtee~~ transient cosmic events reported for last 2-3000 y: mostly comets but some "new stars" or "guest stars": suddenly appear; visible in daytime ~ days-wks; vis. for several y; disappear in few ~~m~~ mos - 2-3 yr. (1006: $V_{max} \sim -9.5$, 1054: $V_{max} \sim -5$, daytime 23 d, visible ~ 22 months).

Established hist. SN (see remnants now):

1006, 1054, 1181, 1572, 1604.

S And 1885: Novae were known but if ~~S~~ And extragal, this was bright! Recognize SN ca 1934 (Baade + Zwicky): ~~Exp~~ → Stellar explosion releasing $\sim 10^{51}$ erg of mech. en.

__Properties of SN:__

$M_B \sim -18^m \pm 2^m.5$ at peak; rise in wks, fade in ~2-3 yr, having radiated $\sim 10^{49} - 10^{50}$ erg in optical (+ lots in other bands).

__Spectra__

H or no H (Type II, Type I).

Broad lines, em + abs. $T_{max} \sim 10^4$ °K, $v \sim 10^4$ km s^{-1}.

SNR as Radio Sources

Properties of I, II: Viewgraph.

Progenitors: Type I: Pop II. (old disk, see in E). White dwarf in binary: ~~[illegible]~~ no stellar remnant.

Type II: Pop I. (sp arms; none in E). Single massive star: ~~[illegible]~~ Make neutron star (pulsar.)

What happens when you hurl off several $M_\odot$ at $\sim 10^4$ km/s into ISM?

Four-phase Evolution.

I. Free expansion. Ejecta expand uniformly ($v \propto r$); spherical "piston" sweeping up, shocking ISM.

$\frac{1}{2} m_p v_s^2 = kT \Rightarrow T \sim 6\times10^9 \left(\frac{v_s}{10^4}\right)^2$ K. Hot!

Collect mass until swept-up mass comparable to ejecta. Then begin deceleration. Occurs when

$\frac{4\pi}{3} \rho_1 R^3 \gtrsim M_{ej}$ $\quad (\sim 400\ n_1^{-1/3}$ yr). So

II. Sedov self-similar blast wave.

Adiabatic: not time for shocked gas to radiate.

Energy conserved. $\rho_2/\rho_1 = 4$.

So eqs of motion

$KE = \frac{1}{2} M \dot{R}^2$; $\frac{d}{dt}(KE) = 0 \Rightarrow M\dot{R}\ddot{R} + \frac{1}{2}\dot{M}\dot{R}^2 = 0$

Mass: $M = \frac{4\pi}{3}\rho_1 R^3$ $\quad (M_{ej} << M_{tot})$

So $\dot{M} = 4\pi \rho_1 R^2 \dot{R}$;

$\dot{R}\ddot{R} + \frac{3}{2}\dot{R}^2 = 0$.

$R \propto A t^r \Rightarrow r = 2/5$. $\quad R \propto t^{2/5}$

$V \propto t^{-3/5}$.

Or similarity solution.

Eventually, shocked gas has time to cool. ~~Then~~ by radiating. Then p drops, compress into thin shell.
Snowplow (radiative) phase. Begin when $V_s \sim 200\ km\,s^{-1}$
$\rho_2/\rho_1 \sim$ hundreds. ($\sim 10^4$ yr)
E not conserved but P is. ($R \sim 10$ pc)
& $\frac{dP}{dt} = 0 \Rightarrow \dot{M}\dot{R} + M\ddot{R} = 0.$
Similar analysis $\Rightarrow$ $r = \frac{1}{4}$ $R \propto t^{\frac{1}{4}}$. (Slower).

IV. Finally $V_s \sim$ tens of km/s - comparable to cloud velocities.
Dissipate shell.

Mention modifications to this picture.
- Ambient medium may be from pre-SN mass loss ($\rho \propto r^{-2}$) - not uniform.
- Early times: Pulsar may blow bubble in interior.
- Discrete clouds in ISM may affect evolution
- Late stages: Mag fields may become dominant pressure.

Turn attention to Radio Emission.
(Other bands: X-ray: often shells, see lines. Thermal. (Young
Optical: filaments only. Get V_s, proper motion can $\Rightarrow r$)

Mentioned shell morphol, nonth spectrum, pol
Show $\Sigma - D$ diagram.

Em. mech: Clearly synchrotron radiation.
If el. distribution is $N(E) = K E^{-s}$ els $cm^{-3}\ erg^{-1}$, $s = 2\alpha + 1$
S_ν ($erg\ cm^{-2}\ s^{-1}\ Hz^{-1}$) $\propto \frac{R^3}{d^2} B^{1+\alpha} K$ ($s > 2$: $\propto \frac{R^3}{d^2} B^{1+\alpha} n_e$)
(J_ν)

So: Where do $\vec{B}$, electrons come from?

I. Ambient, compressed field + cosmic rays?
See galactic synchrotron background:
obs $j_\nu \sim$ ~~xxxx~~ 10^{-25} Jy cm^{-1} (arcmin)$^{-2}$. (21 cm)
Tycho: 42 Jy $\Rightarrow j_\nu \sim \underline{4 \times 10^{-20}}$ Jy cm^{-1} (arcmin)$^{-2}$!
Cyg Loop: $j_\nu \sim 30 \times j_\nu$ (backgr).

(Adiabatic)
Young remnants: Get factor $\underline{\underline{4}}$ compression only!
$\underline{K} \uparrow$ by 4, $B \uparrow 4$ (max possible)
$\Rightarrow j_\nu \uparrow$ by $4^{2+\alpha} \sim 40$ max

Old remnants: Can have much larger compressions in cooling shocks $\Rightarrow$ OK.

Where do extra B and/or n_e(rel.) come from for young SNR?

II. Shell, + coinc. w/ x-ray, opt (thermal, shock-heated material) $\Rightarrow$ at or near shock,
accelerate relativistic electrons and/or
amplify magnetic field.

How decide how much of each?

later [Ty: If B compressed only, need 100 x en. dens in ambient cr's! That's els only. If ~~xx~~ protons have 100 x as much en (as obs at earth), Ty puts ~ 100% of its en into cr's!]

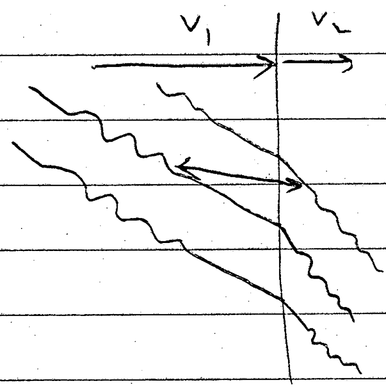
Shock Acceleration of Relativistic Particles

Ball bouncing off approaching wall gains energy.

Fermi 1949: Particles bounce off random interstellar clouds: some approach, some recede. Effects don't quite cancel.

$\Delta E = 0 + \mathcal{O}(\frac{v}{c})^2$. Second-order.

But: Shock wave.



$\vec{B}$ with wiggles convected through.

Electron bouncing off wiggles back & forth can be caught between 2 approaching walls.

$\Delta E \sim \mathcal{O}(\frac{v}{c})$. First-Order Fermi Accel.

Can show that under wide range of assumptions, this gives $N(E) \propto E^{-2}$ or a little steeper – as observed!

Don't know how efficient this is.

Field Amplification: Viewgraph.

Physics: Turbulence ... ?? Sharp shocks in Tycho, SN1006
⇒ begins right at shock!

List problems with young remnants (viewgraph).

SN1006: E_{max}? x-rays north?

Crablike SNR

We've left out most famous SNR. SN1054

Odd because

1) center-brightened morphology
2) flattish spectrum - $\alpha \simeq 0.25$
3) X-rays ~~pow~~ non-thermal (also ∃ opt contin.)

We also know Crab Nebula contains pulsar.

See several other sim. (exc. pulsar!) (viewgraphs)
(but only few % of all SNR)

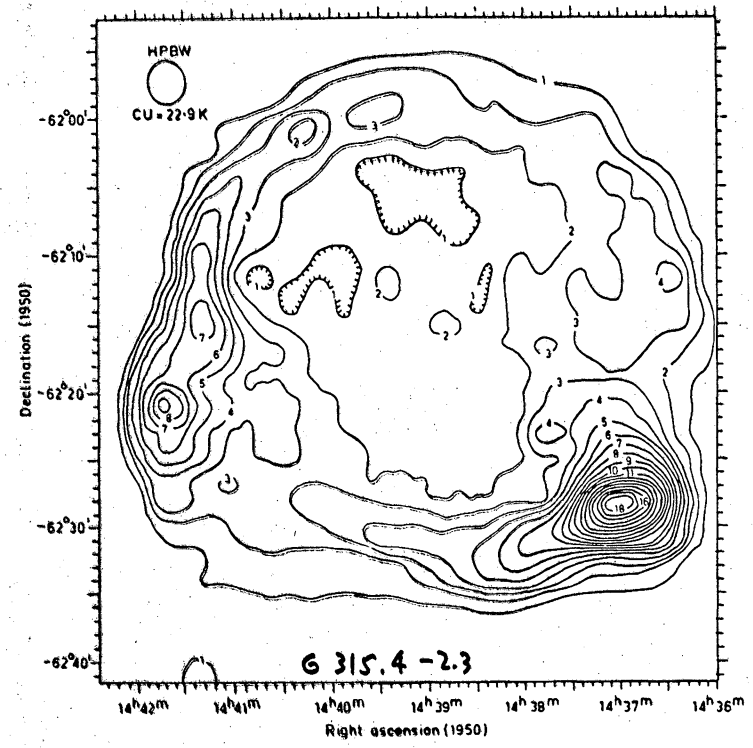
Explain as pulsar bubble blown inside ejecta - don't see outer shock at all yet.

Describe bubble structure (viewgraph).

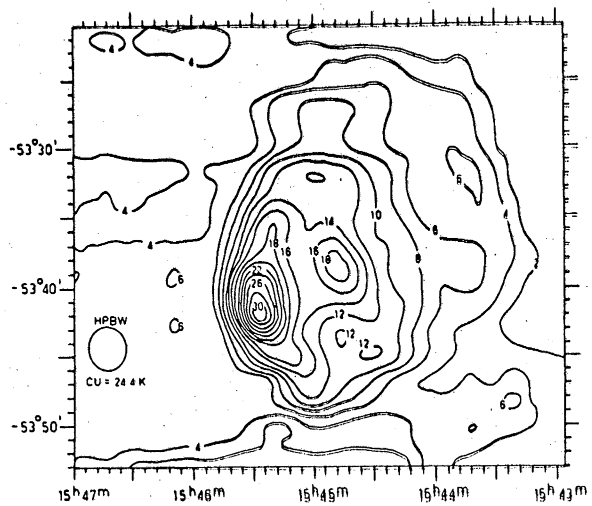
Calculate brightness evolution.

Objects fade fast - perhaps fast enough that all SN II could produce - but perhaps not. (M31 obs project!)

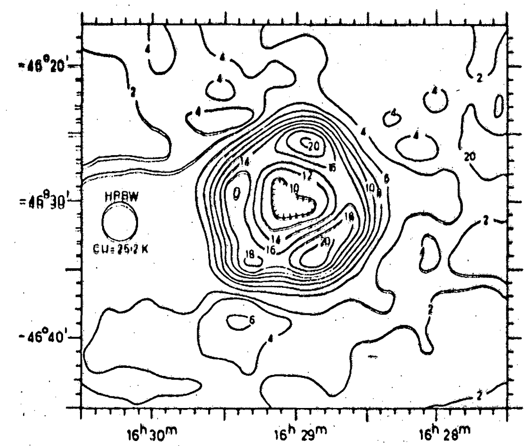
Caswell, Clark + Crawford 1975 Aust. J. Phys. Supp., No. 37, p. 39
408 MHz maps



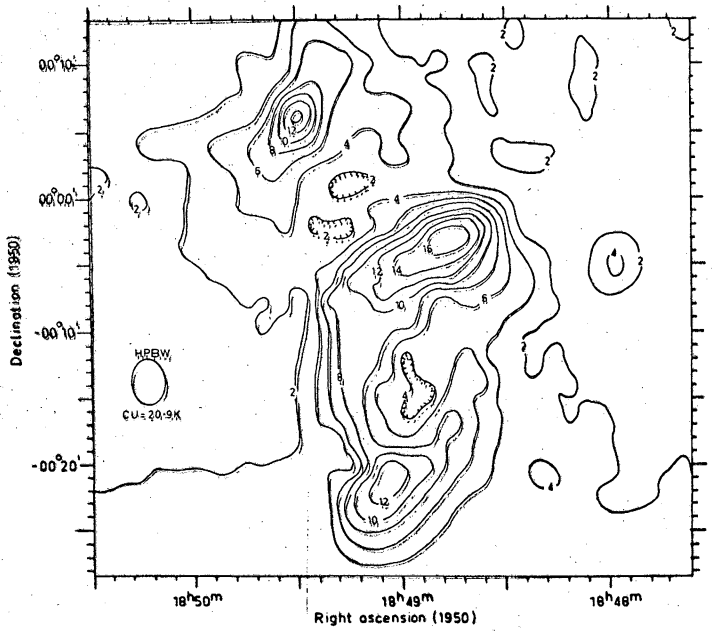
G 315.4 -2.3

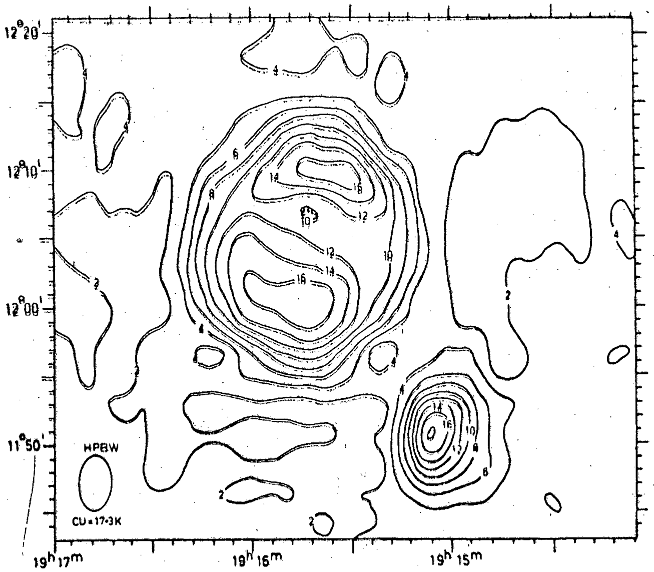


G 327.4 +0.4



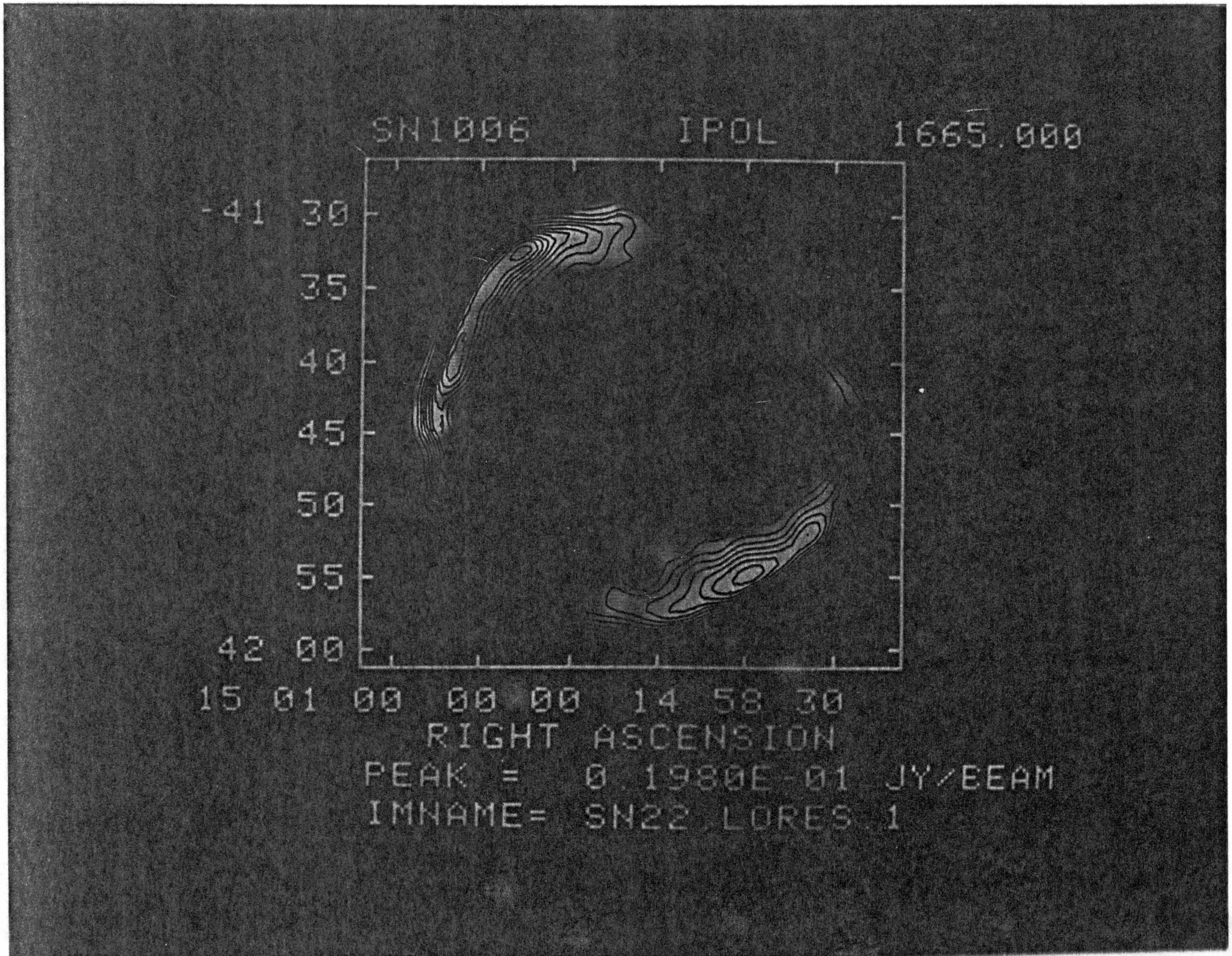
G 337.3 +1.0



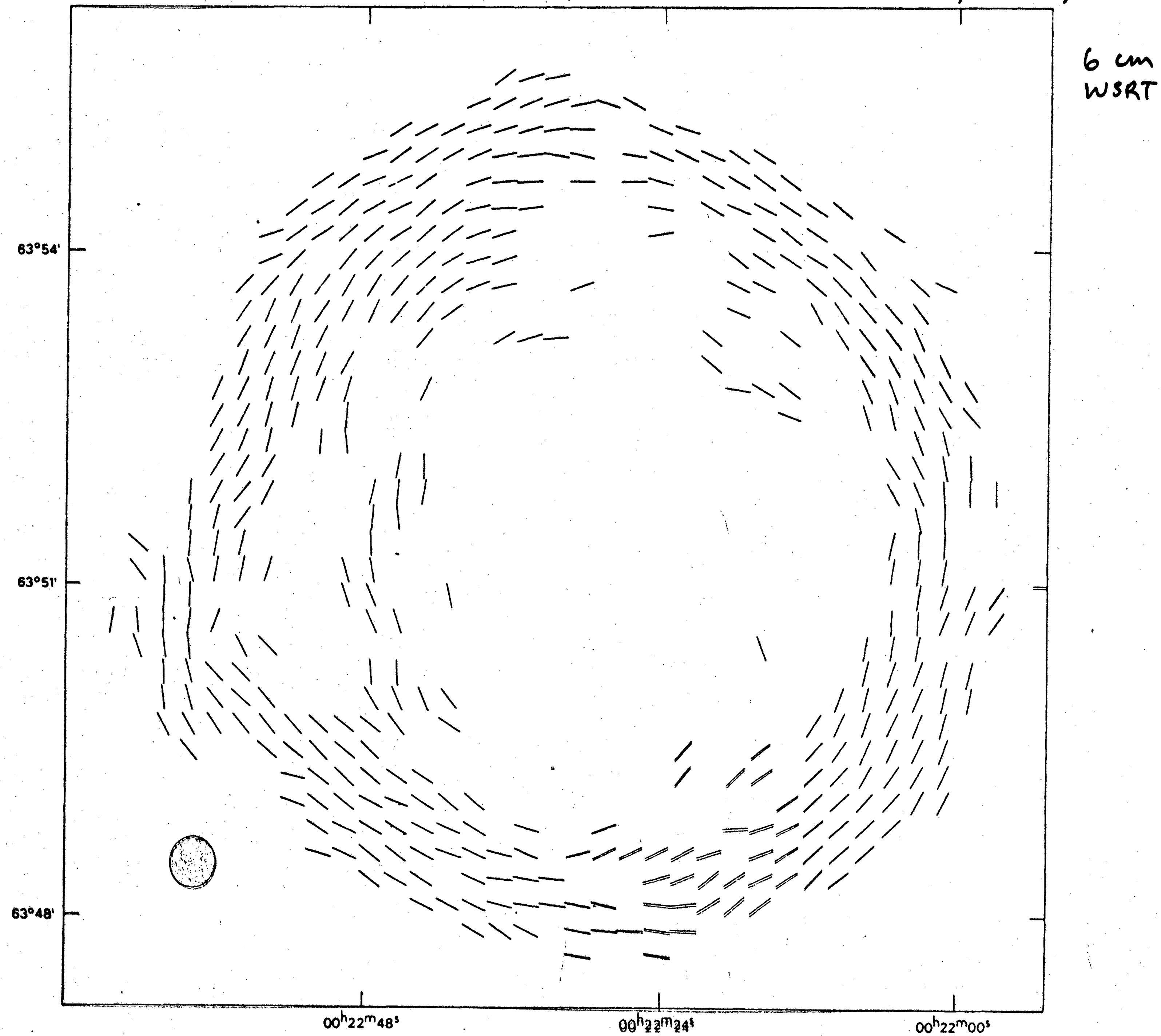


G 46.8 - 0.3

Grey-scale: Radio. Contours: X-rays.

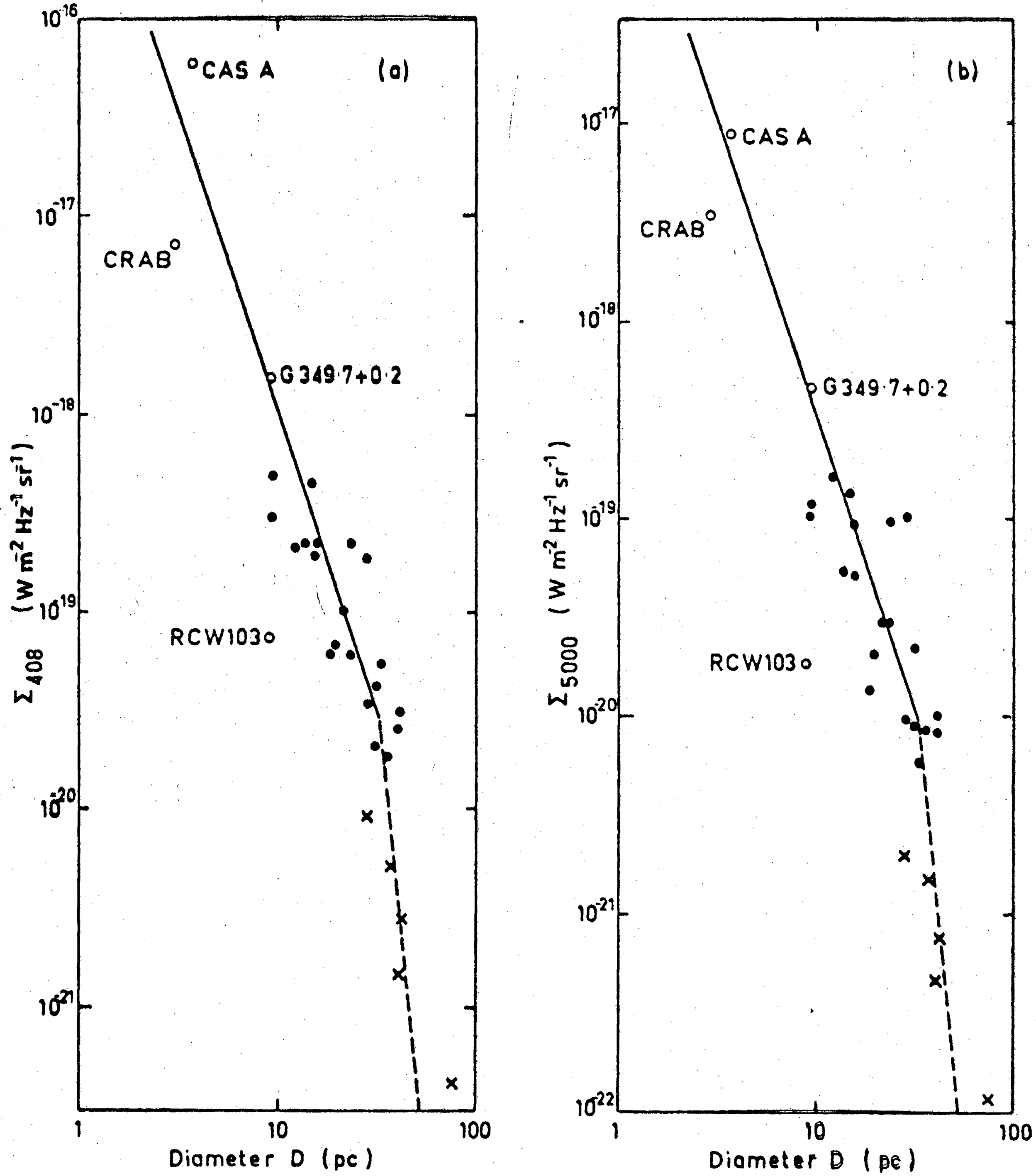


Intrinsic (de-rotated) E-vectors in Tycho's SNR. Duin + Strom 1975, AA, 39, 33.



Properties of Supernovae

	Type I	Type II
Ejected Mass ($M_\odot$)	0.5	5
Mean velocity ($km\ s^{-1}$)	10,000	5000
Kinetic energy (erg)	5×10^{50}	1×10^{51}
Visual radiated energy (erg)	4×10^{49}	1×10^{49}
Ionizing radiated energy (erg)	10^{44} or 10^{48-49}	$10^{48} - 10^{49}$
Frequency (yr^{-1})	1/60	1/40
Stellar population	old disk	young disk
Progenitor	white dwarf in binary?	massive single star

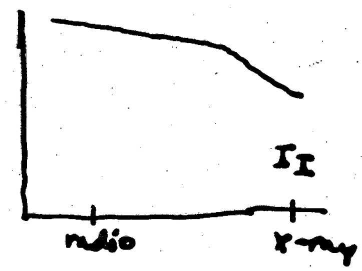


Clark + Caswell 1976, MNRAS, 174, 267.

Swept-up or Amplified Field?

1) <u>If</u> particles are accelerated to very high energies:

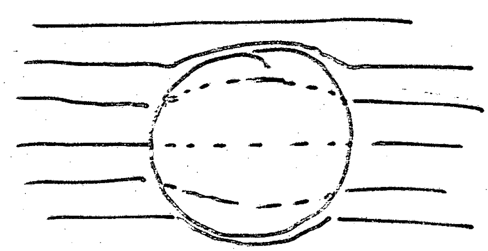
$B \sim 4B_0 \Rightarrow$ break frequency from SR losses is so high that predict $\sim$ <u>100 ×</u> too much X-ray flux.



2) Even if E_{max} too small for X-rays:

$B_0 \sim 3 \mu G \Rightarrow$ need $\gtrsim 2\%$ of ρV_s^2 in relativistic electrons. <u>Protons</u>? (cr's: $\frac{N_+(E)}{N_-(E)} \sim 100!$)

3) Swept-up field should be primarily <u>tangential</u> (van der Laan '62) but obs. $\Rightarrow$ <u>radial</u>

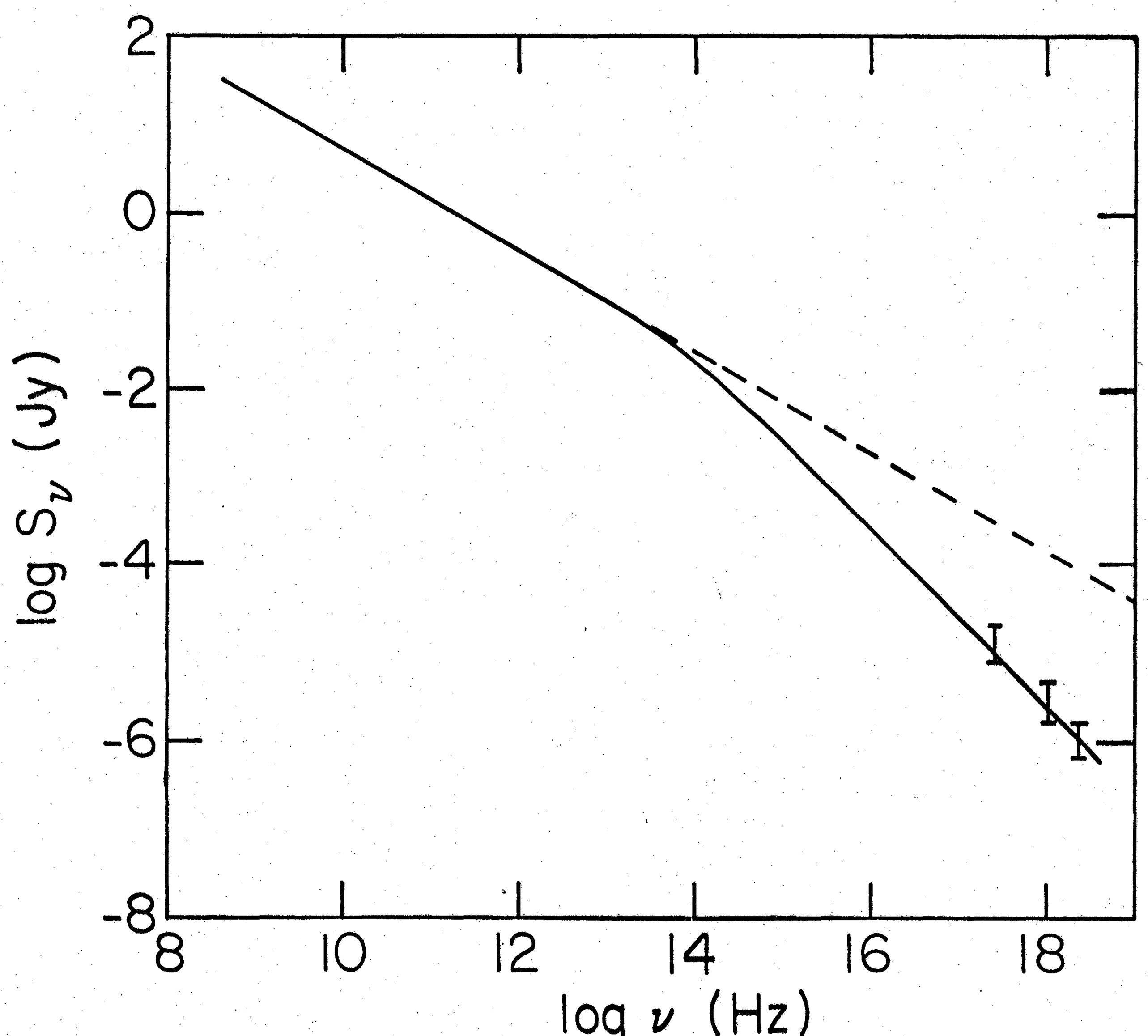


4) Swept-up field $\Rightarrow$ predict $\frac{dS_\nu}{dt} = 0$! $(\Sigma \propto D^{-2})$

a) Too flat Σ-D slope

b) <u>Tycho</u>: Amplified field predicts $\frac{\dot{S}}{S} = 0.25\ \%\ yr^{-1}$

<u>Obs</u>: Strom <u>et al</u> 1982: $\frac{\dot{S}}{S} = 0.23 \pm .19\ \%\ yr^{-1}$



Model spectrum of SN1006 : Reynolds and Chevalier 1981, ApJ, 245, 912.

I : IPC X-ray observations.