TheYin and theYang of Colliding Flows

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Examples of Useful Contrasts:

- radio vs. X-ray frequencies
- thermal vs. nonthermal emissivity
- adiabatic vs. radiative cooling
- homogeneous vs. clumpy structure
- ram vs. magnetic shock confinement

See in perfect high-definition contrast?
vs***:***
Know an elephant by its trunk and tail?

Colliding Wind Questions

What can we learn about stellar winds by watching them ram into things?

What do radio and X-ray observations tell us about these collisions?

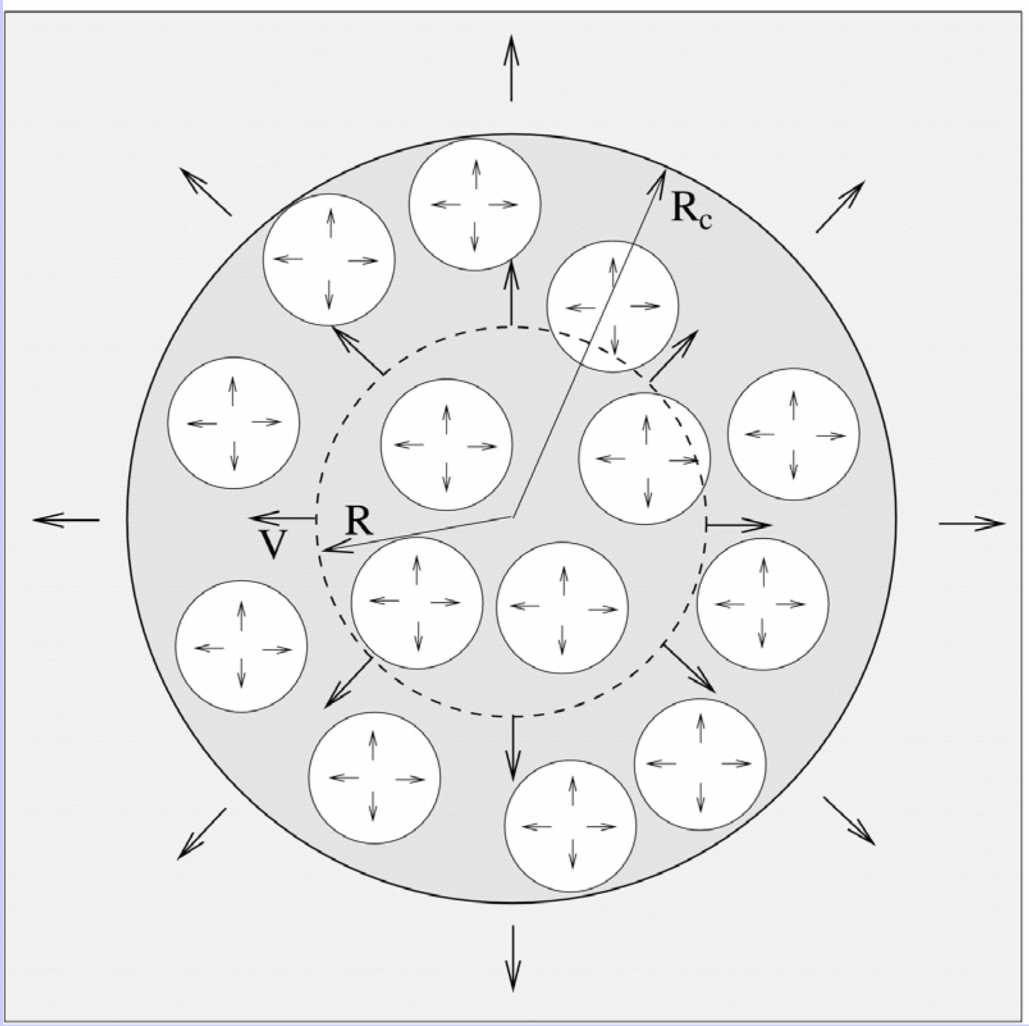
Which diagnostics are most sensitive to which physical processes?

Learn from Colliding Flows:

- Mass flux
- Momentum flux
- Energy flux
- Global and local magnetic fields
- ISM or molecular gas encounters

These are the elephants– how much of them can we see using X-ray and radio?

Cluster-Flow Superbubbles

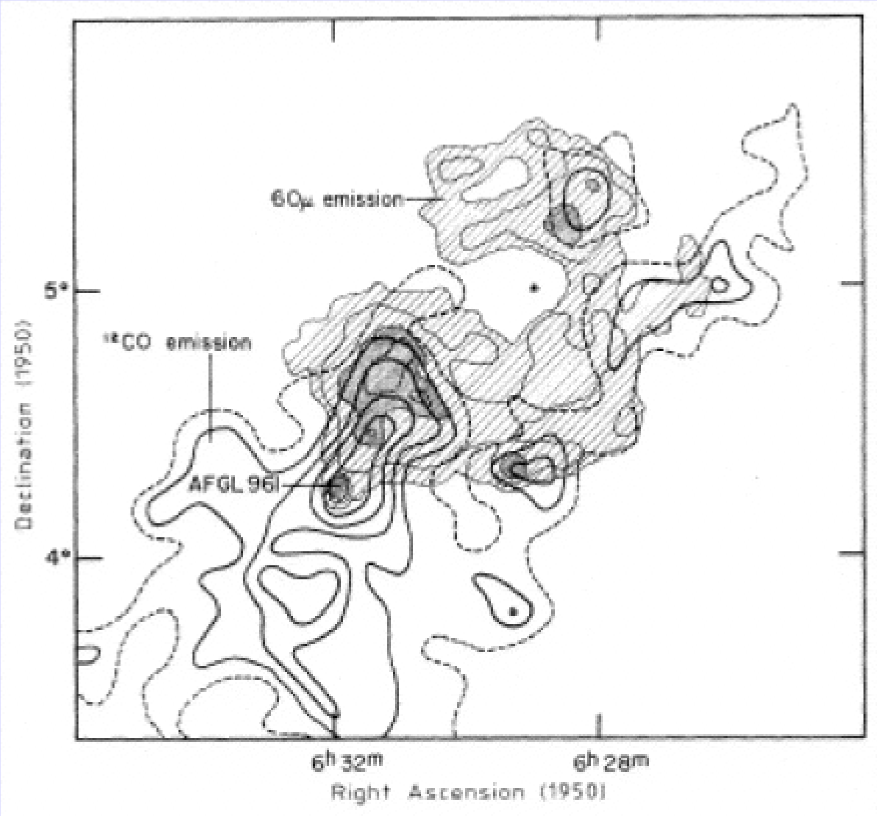


(Canto, Raga, & Rodriguez 2000) Many stellar winds are shocked and thermalized into a single giant pressure-driven superwind. Potential X-ray source (Mac Low et al. 1998).

Bubbles Blown by Outflows

- Stellar winds and SN are the source of radial momentum and energy flux
- Shocks thermalize the energy, heating the gas and raising the sound speed
- When the flow goes subsonic, the density rises, enhancing the momentum flux (i.e., pressure)
- This enhanced momentum flux is transferred to a thin swept-up shell of radiatively cooled ISM

Cluster-Flow Boundary in CO



Townsley et al. (2003)
Rosette nebula

The Good News

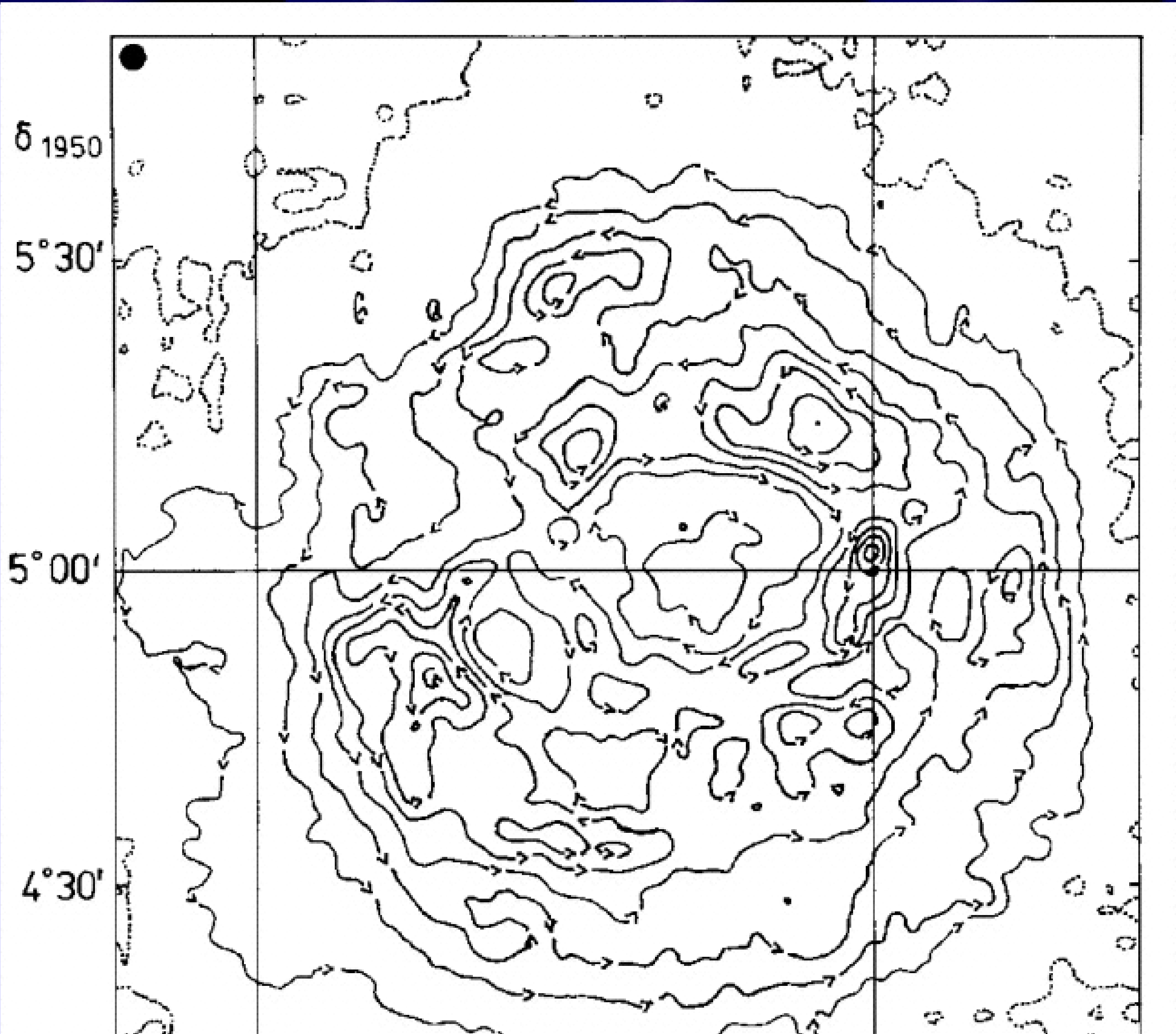
For radio:

- ***ultra low attenuation***
- ***excellent spatial resolution***
- ***thermal free-free signatures***
- ***nonthermal diagnostics of acceleration***

For X-rays:

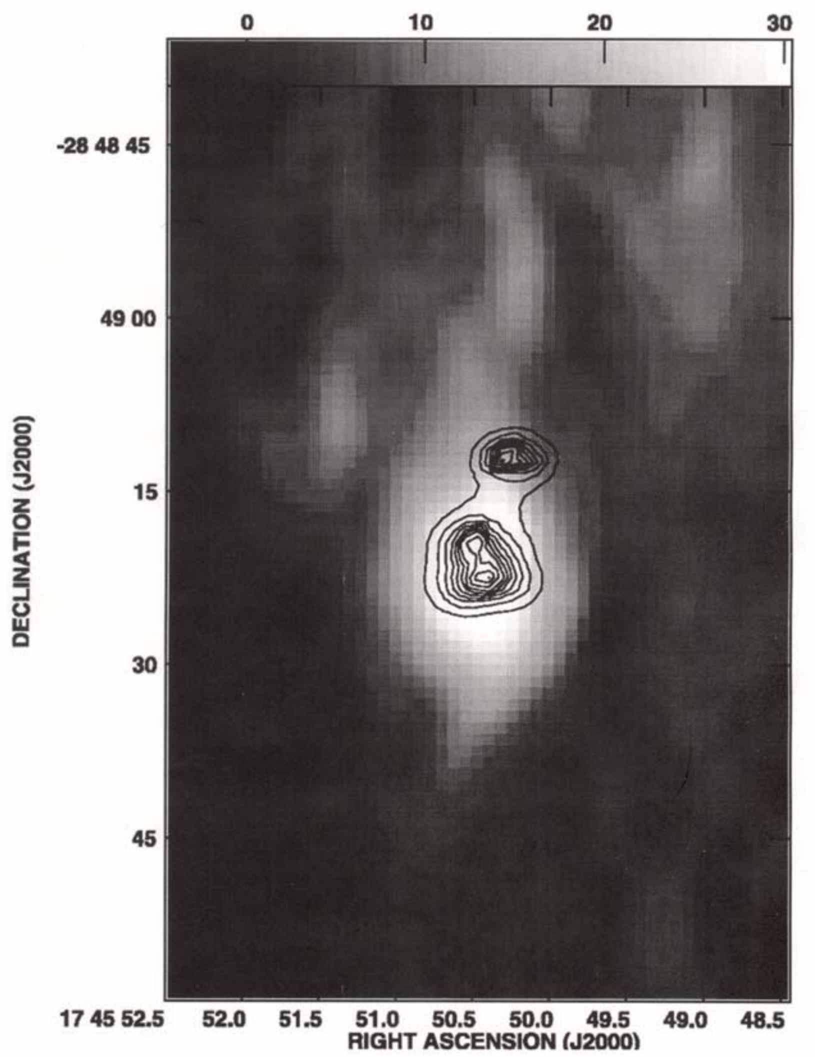
- ***fairly low attenuation***
- ***important energy channel for hot gas***
- ***temperature-sensitive spectral lines***

Rosette Nebula Radio Map



Townsley et al 2003

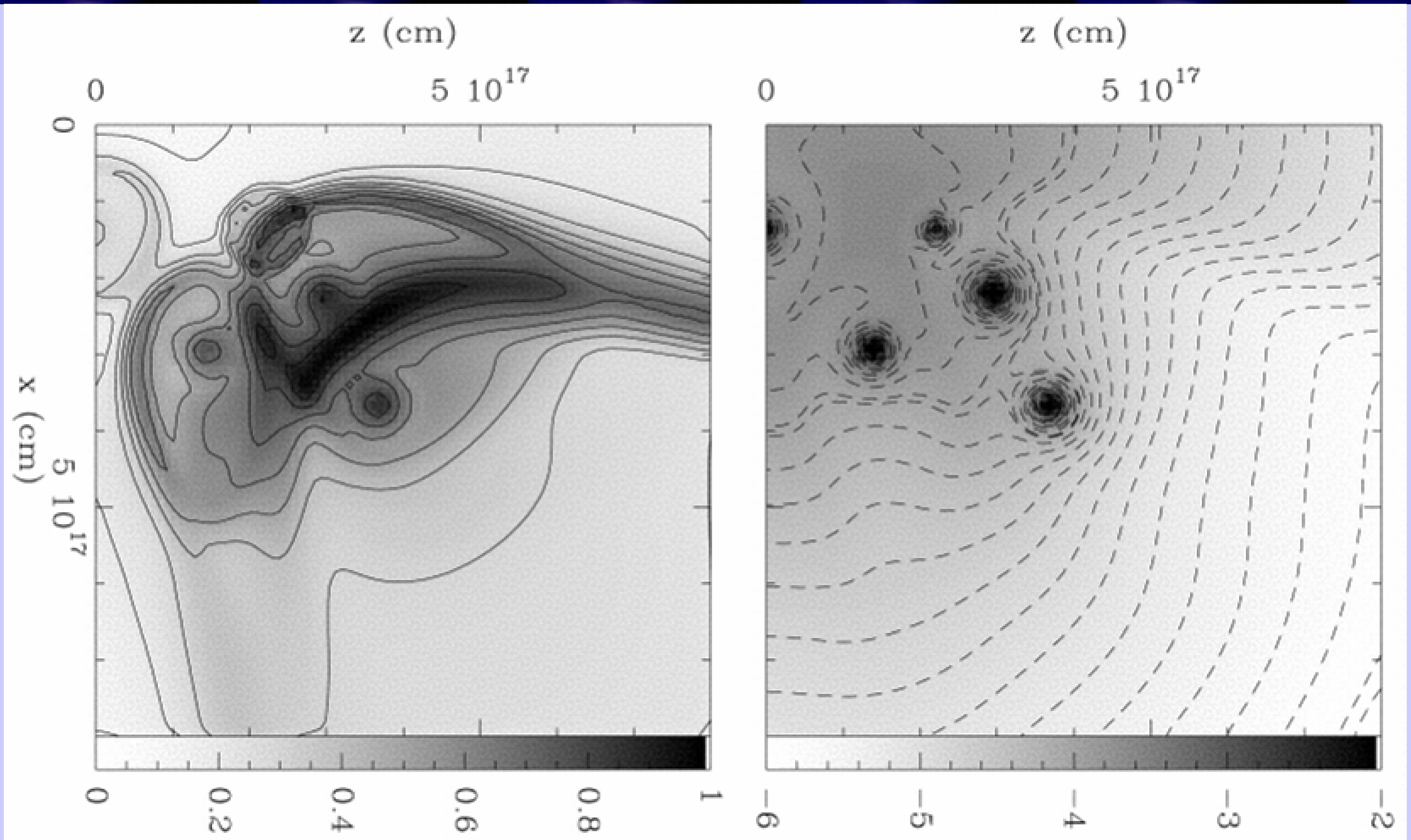
“Arches” Nonthermal Radio



From Yusef-Zadeh et al. (2003)

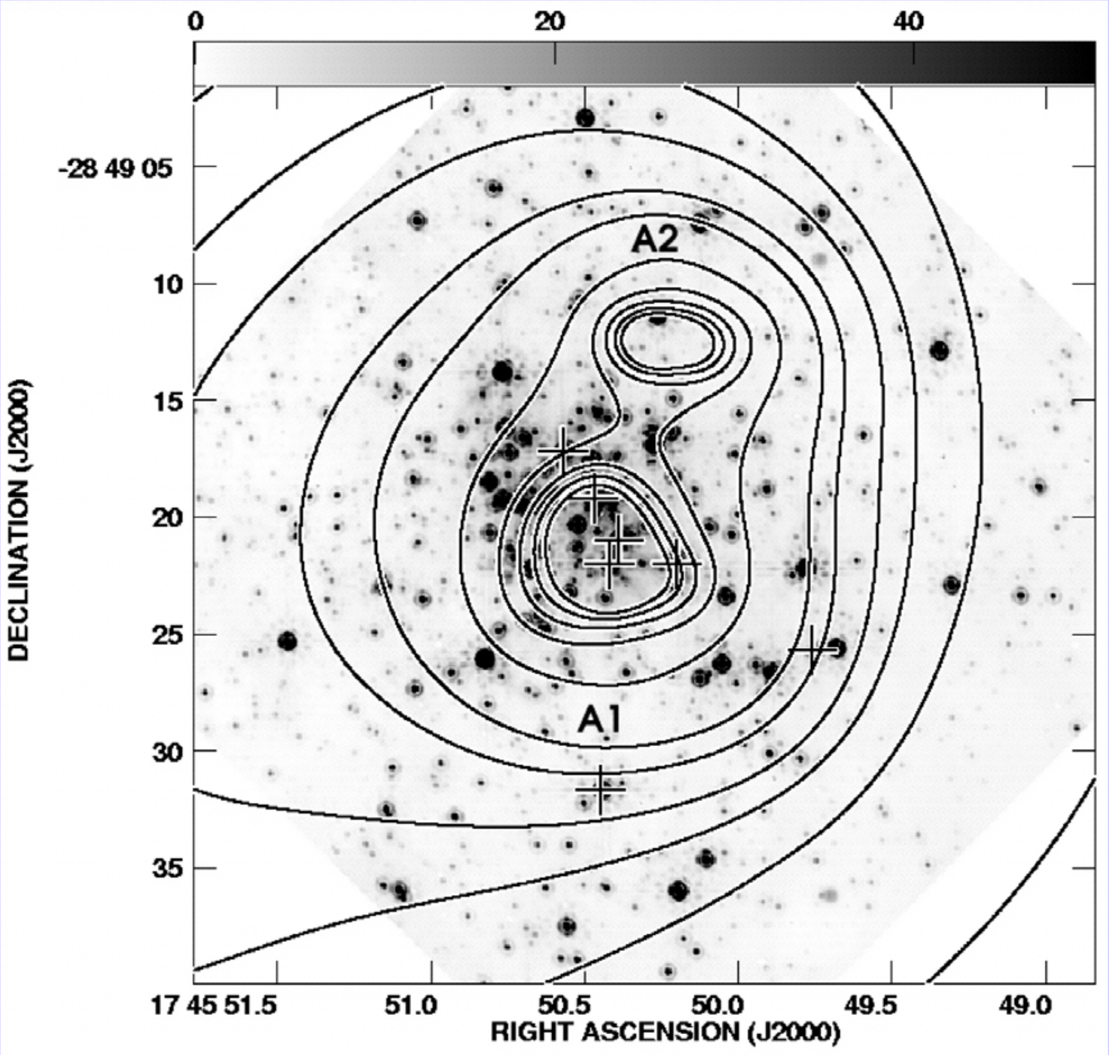
Nonthermal radio has a diffuse character, indicative of particle acceleration in colliding wind shocks. Thermal X-ray contours are superimposed.

Predicting Cluster X-rays



From Canto, Raga, & Rodriguez (2000)

Arches Diffuse X-rays Seen



From Yusef-Zadeh et al. (2002).

ACIS observation of the Arches cluster. Stars are superimposed.

The Not-So-Good News:

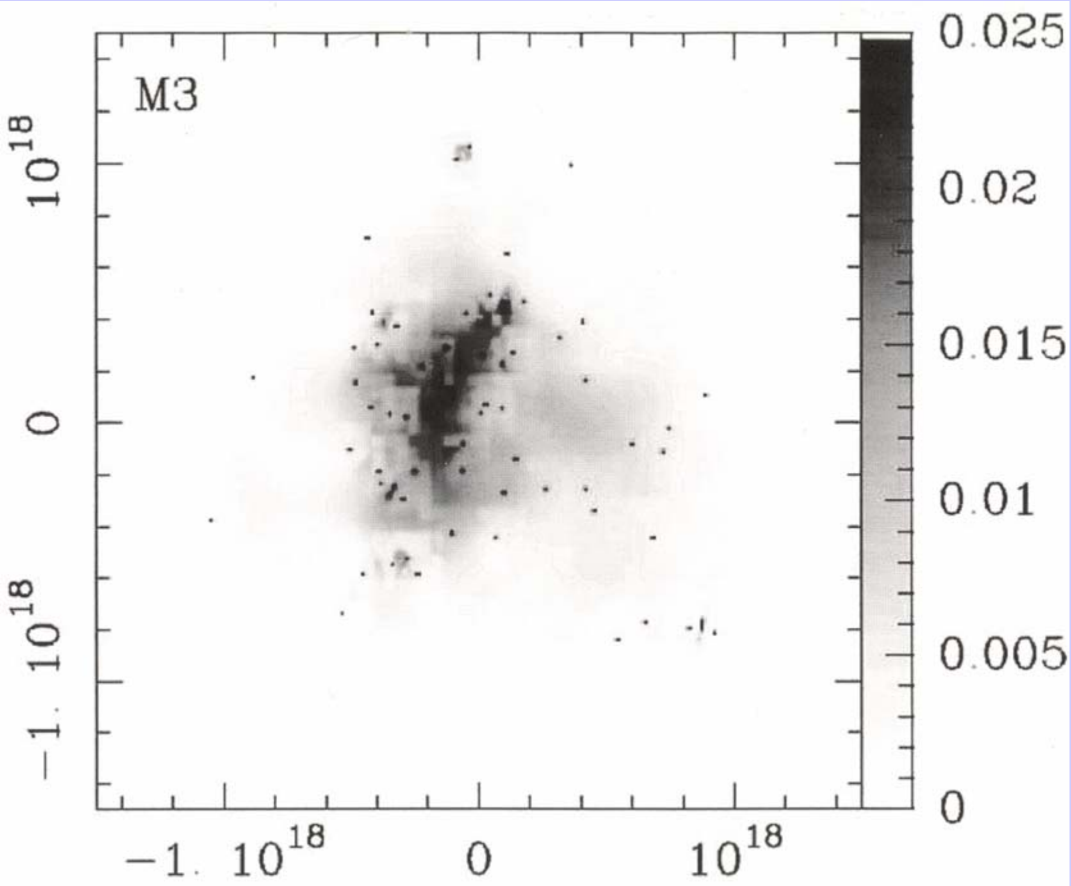
For radio:

- ***uncertainty in acceleration and B fields***
- ***thermal emission is a weak energy component***
- ***density-squared sensitivity to clumping***

For X-rays:

- ***self-absorption may remove some sources***
- ***trace energy channel when nearly adiabatic***
- ***again the density-squared clumping sensitivity***

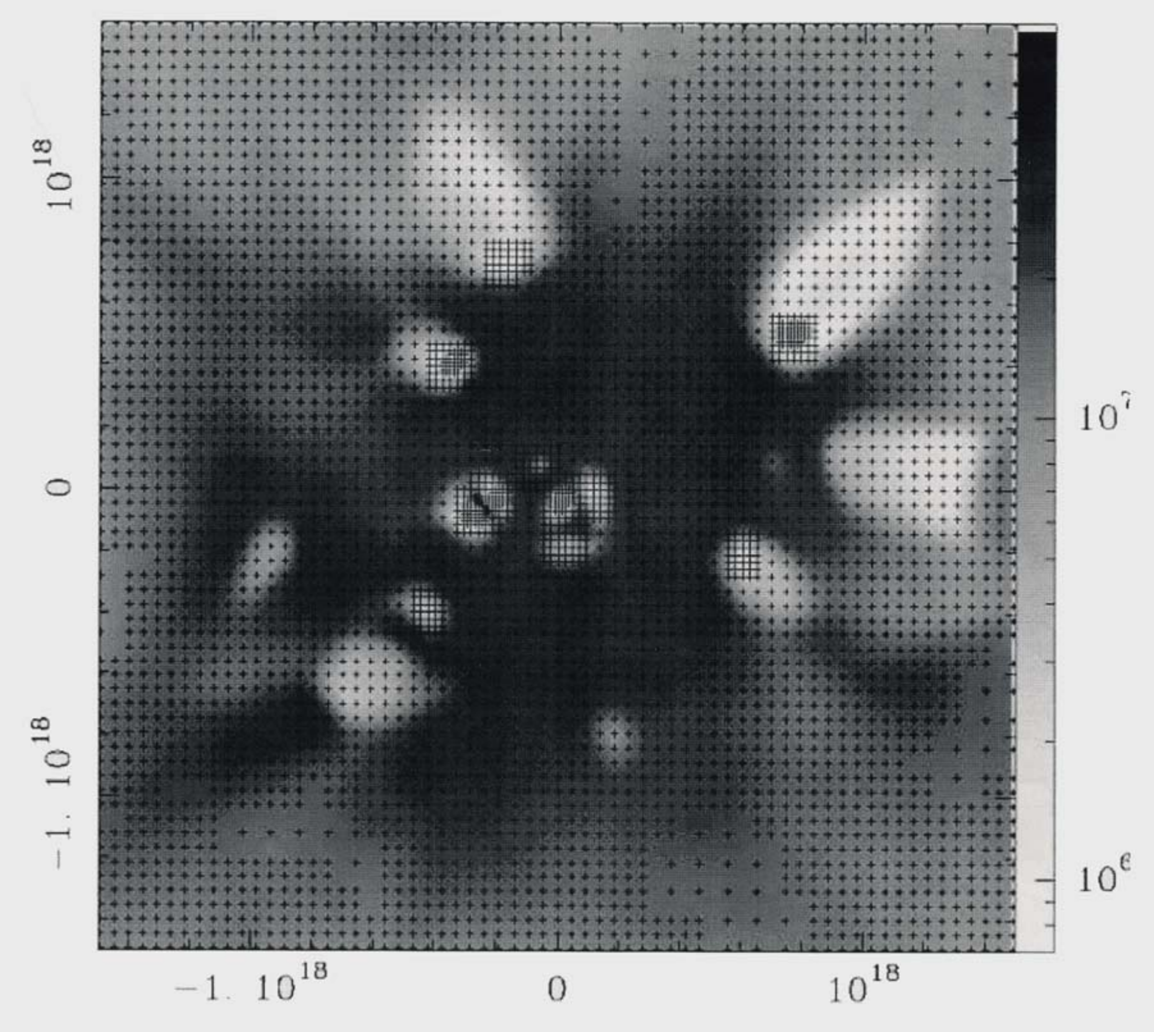
Simulation of “Arches” X-rays



Simulated diffuse X-rays for “Arches” cluster model. Agreement with observations (Yusef-Zadeh et al. 2002)
is quantitative only for extreme stellar-wind mass loss.

From Raga et al (2001)

“Arches” Outflow Simulation



From Raga et al. (2001)

Temperatures of warm stellar winds and hot shocked gas for conditions similar to the Arches cluster.

The simulation is low resolution so might miss turbulent clumping.

Good/Bad News for Adiabaticity

Cluster outflows with $n_e \approx 10^{-2}\,\mathrm{cm}^{-3}$ are expected to be primarily adiabatic.

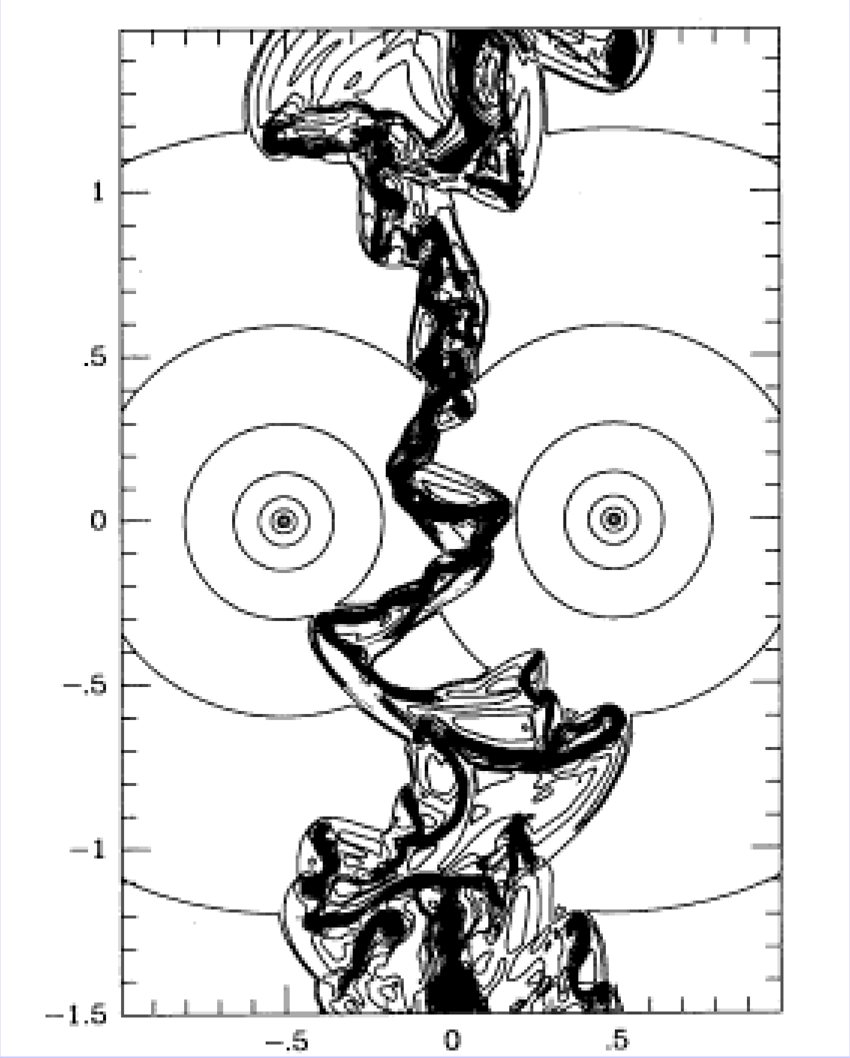
The good news:

- energy bookkeeping is made easier
- gas gets hot enough to emit X-rays
- high pressure resists clumping

The bad news:

- bulk of energy is not directly observable
- radiative efficiency becomes a critical parameter which is sensitive to clumping and ionization

Radiative Cooling Instability



From Stevens, Blondin, & Pollock (1992).

Thin-shell instability in strongly cooled colliding stellar winds

Adiabatic Instabilities

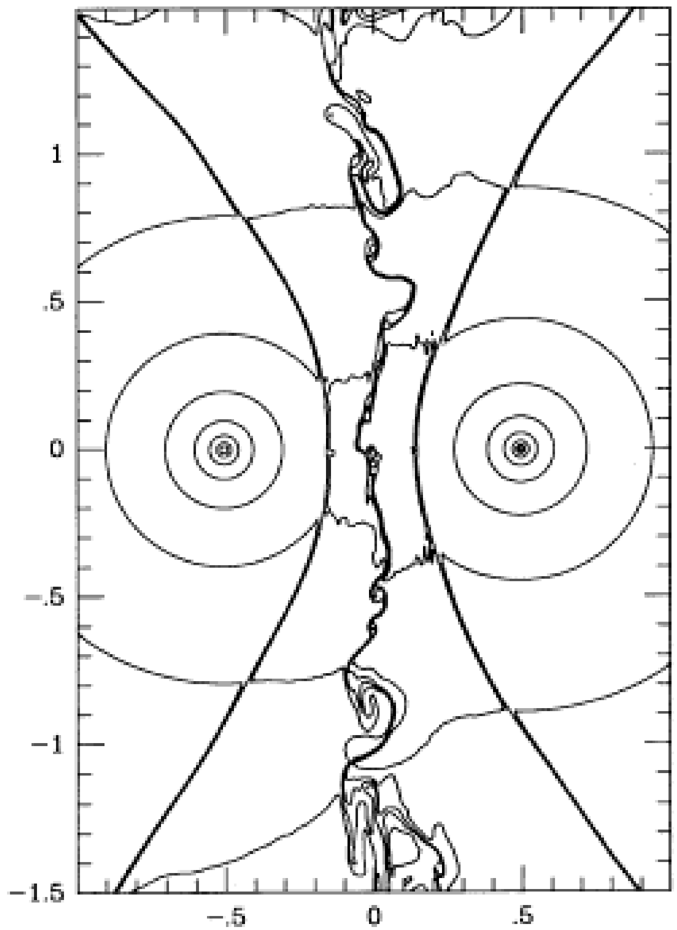


FIG. 6.—Example of the Kelvin-Helmholtz instability of the contact discontinuity separating two adiabatic winds with different velocities but equal momentum fluxes. The wind velocities differ by a factor of 2. The density contour lines are spaced logarithmically by a factor of 2. The axes are labeled

Adiabatic flows resist clumping, but are subject to the Kelvin-Helmholtz instability in the presence of velocity shear.

From Stevens, Blondin, & Pollock (1992)

Patterns and Turbulence

Importance of clumping motivates a better understanding of compression and turbulence:

- Patterned compression (standing shocks, slowly propagating working surfaces) could yield geometry dependence and intermittency

- Compressible turbulence involving scale-invariant perturbations gives a log-normal density profile

But either way, the potential for strong clumping implies that a tiny fraction of the mass may be responsible for the observed emission

Density Distributions

In general:

$$\int d\rho \frac{dV}{d\rho} = V$$

$$\int d\rho \frac{dV}{d\rho} \rho = M$$

$$\int d\rho \frac{dV}{d\rho} \rho^2 = EM$$

Define characteristic densities:

$$\int_0^{\rho_V} d\rho \frac{dV}{d\rho} = \frac{V}{2}$$

$$\int_0^{\rho_M} d\rho \frac{dV}{d\rho} \rho = \frac{M}{2}$$

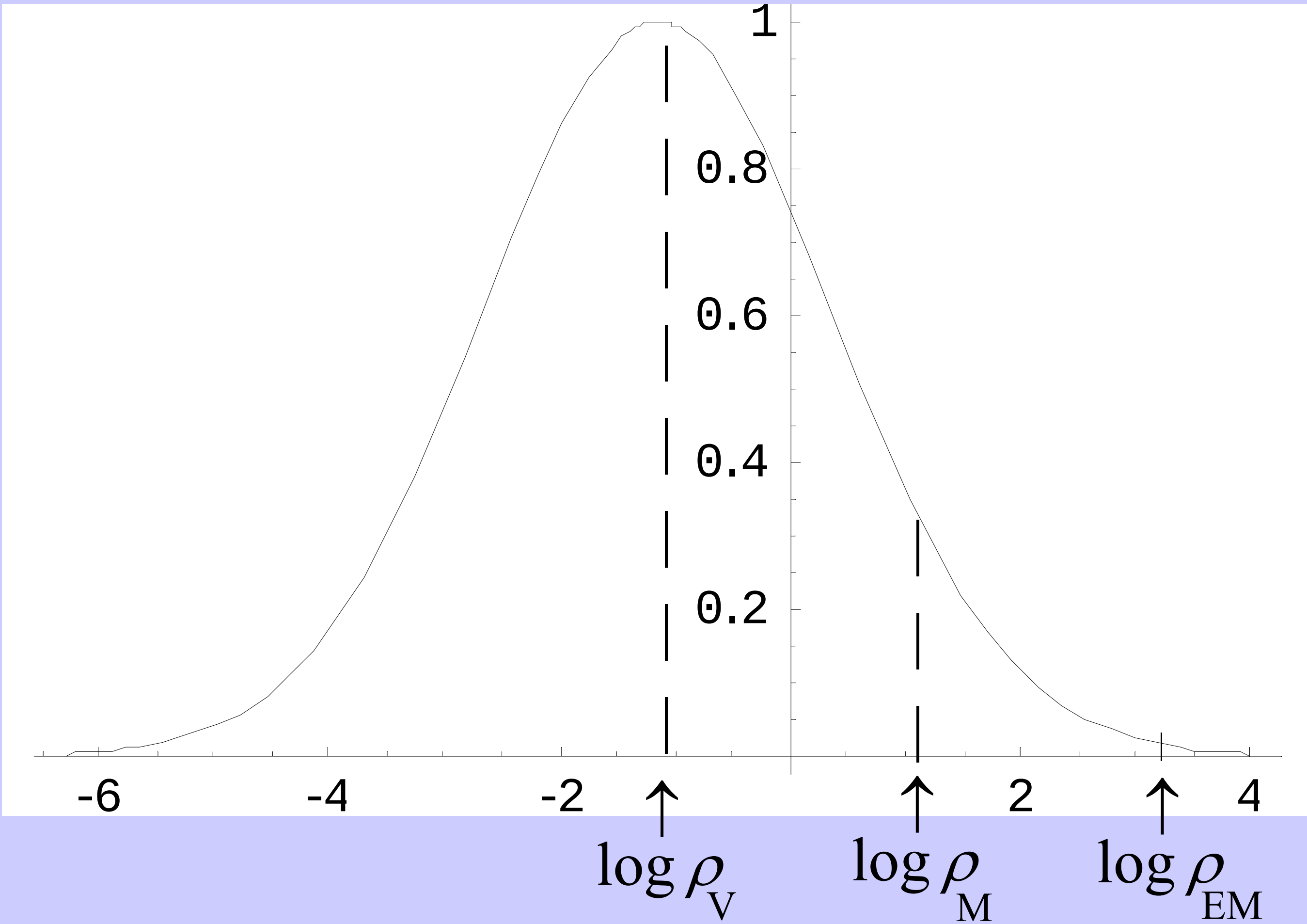
$$\int_0^{\rho_{EM}} d\rho \frac{dV}{d\rho} \rho^2 = \frac{EM}{2}$$

Log-Normal Density Clumping

$dV/d\log\rho$ is Gaussian, since it is obtained via random steps in $\Delta\log\rho$

- yields a drop in median density, while small volumes contain most of the mass
- emission measure is from even smaller volumes with very high density
- this decouples amount of emission from amount of mass
- …the elephant again?

Density Moments for Log-Normal



Contrast with Single Filling Factor

mass filling factor:

$$\eta = \frac{V_M}{V} = \frac{M}{\rho_M V}$$

emission filling factor:

$$\alpha = \frac{V_{EM}}{V} = \frac{EM}{\rho_{EM}^2 V}$$

single filling factor:

$$V_{EM} = V_M$$

and therefore:

$$\alpha = \eta$$

but for log-normal:

$$V_{EM} = \eta^3 V_M$$

so in this case:

$$\alpha = \eta^4 \textbf{ !}$$

Scaling with Filling Factor

If emission measure (EM) and volume (V) are observed:

		one-component clumps:	log-normal clumps:
ρ_{V}	scales as:	$=0$	η^{2}
ρ_{M}	scales as:	$\eta^{-\frac{1}{2}}$	η^{0}
ρ_{EM}	scales as:	$\eta^{-\frac{1}{2}}$	η^{-2}
M	scales as:	$\eta^{\frac{1}{2}}$	η^{1}

Wind Energy or Momentum?

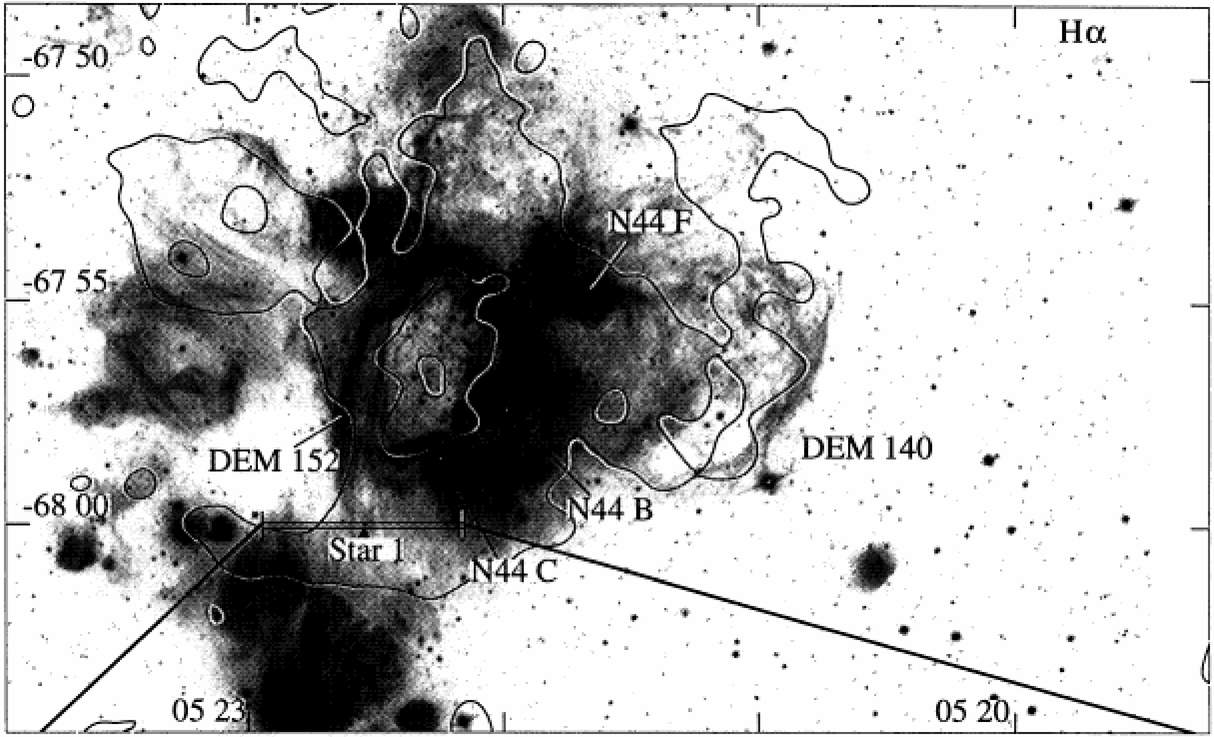
- Input momentum flux is relevant for highly directed (i.e. supersonic) flows, so when:
  bubble flow energy >> thermal energy
- Input energy flux is relevant for isotropic (i.e. subsonic) gas, so when:
  bubble flow energy << thermal energy

This is because isotropic particles must in effect be bouncing off some containing boundary multiple times, delivering their momentum ***each time***. Bulk flows deliver theirs only once.

Limits to the Momentum Flux

- Cluster outflows are thermalized by wind/wind collisions– don’t need boundary
- However, farther from the stars, adiabatic cooling creates a need for re-thermalization by some ISM boundary
- “Holes” in the boundary will inhibit this re-thermalization, thus pushing up the Mach number and driving toward the inefficient limit of momentum-flux conservation.
- ISM structure or SNe can “pop” a bubble

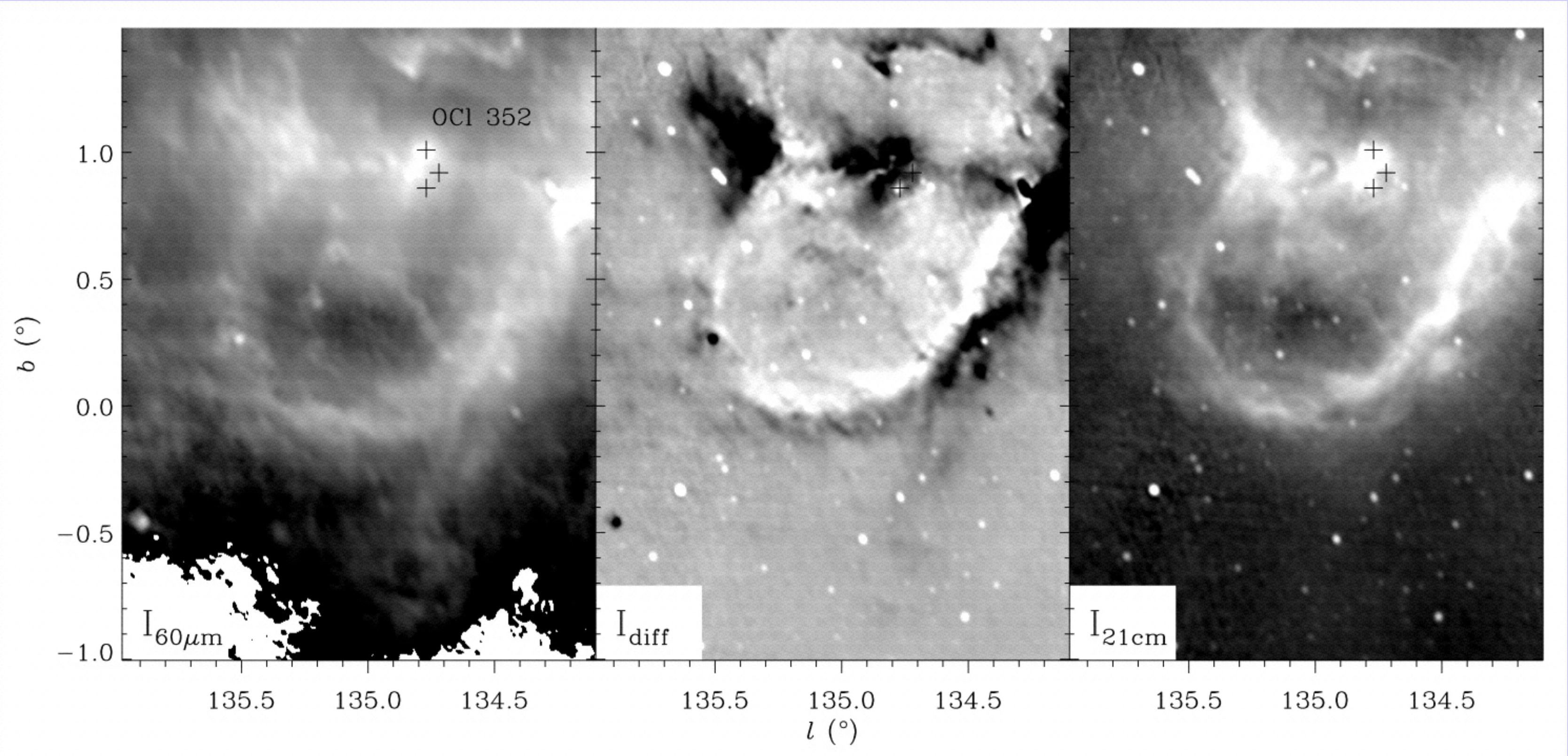
A Blowout in N44?



From Magnier et al. (1996)

Creation of a Galactic Chimney

From Terebey et al. (2003)



Left: IR emission from dust. **Right:** 21 cm emission

Center: difference between left and right

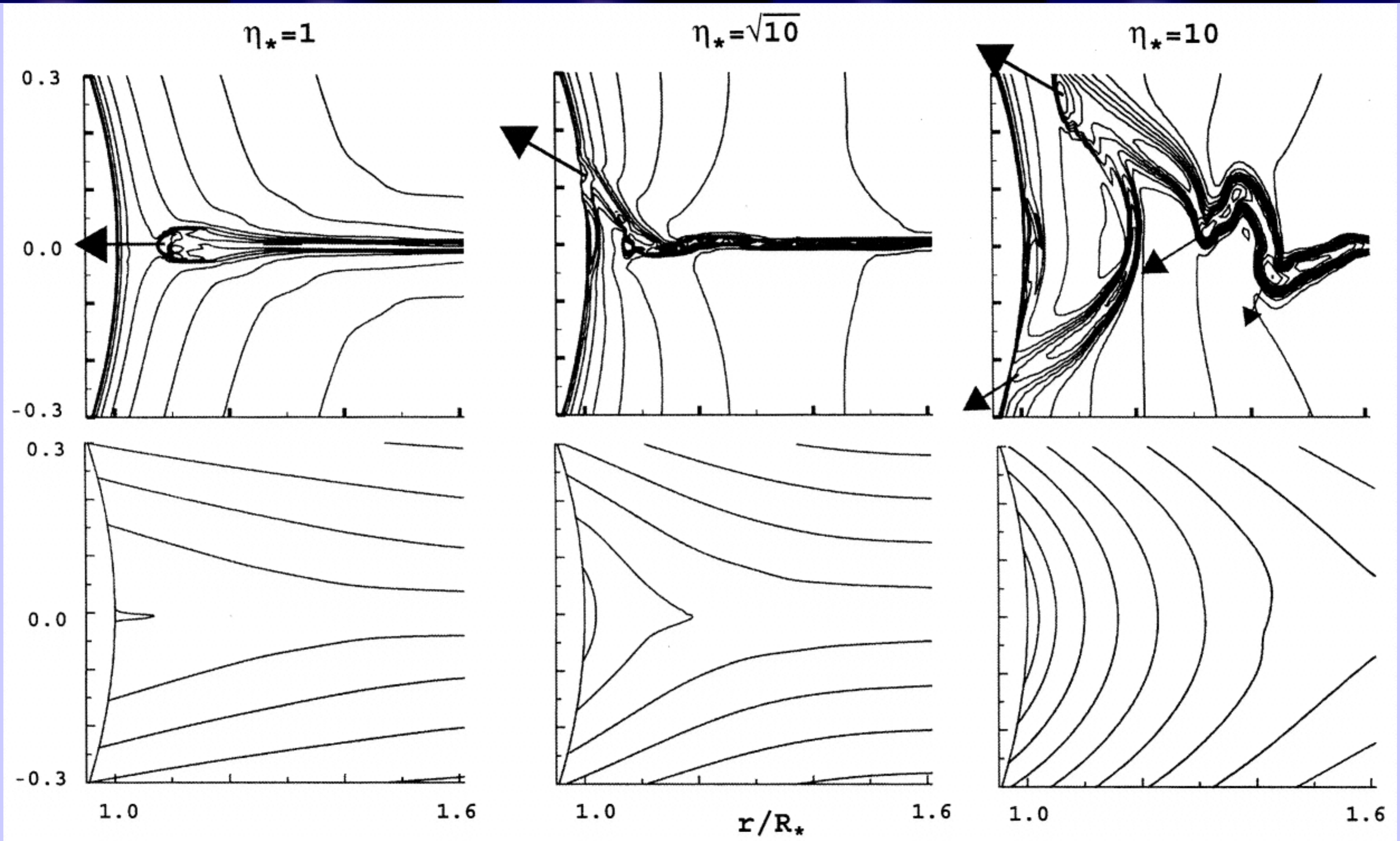
Other Ways to Stall Bubbles

- Most bubble mass is often evaporated from ISM
- Bubble expansion may also be stalled via the effects of mass entrainment (e.g., Pittard, Dyson, & Hartquist 2001)
- Ablation or evaporation from embedded clumps adds mass and lowers T (e.g., Silich et al 1996)
- Standard model still applies fairly well in the absence of SNe near shell (Chu et al 1995)

B Fields vs. Ram Pressure

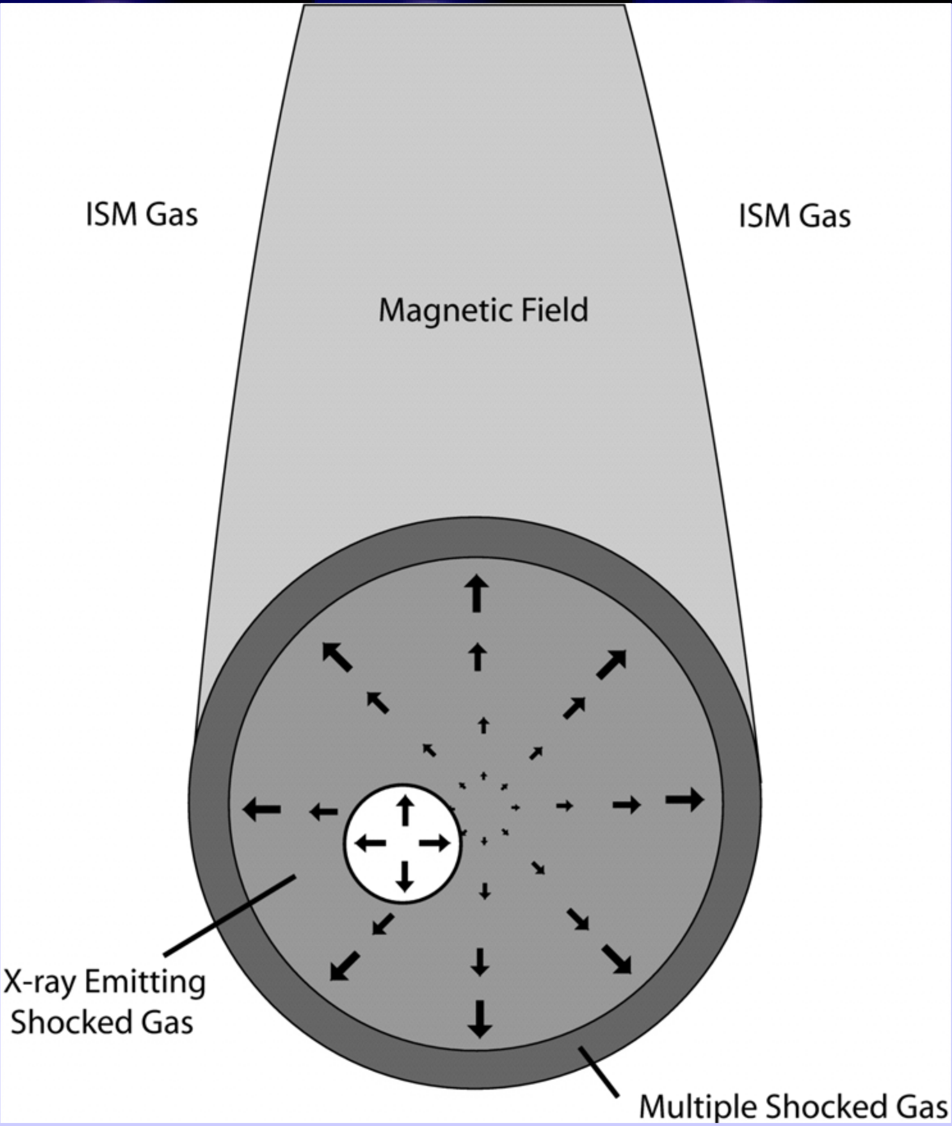
- Zeeman splitting in molecular clouds gives $B \leq 10^{-3} G$
- synchrotron emission from cluster outflows
- B affects dynamics when $v_A \geq v$, so when $B \geq 6 \times 10^{-4} \sqrt{n}$
- may matter close to star where $B \leq 10^{2} G$, or far from cluster core where $n_e \approx 10^{-2}\ \mathrm{cm}^{-3}$
- May explain radio filaments (Yusef-Zadeh 2003), and might also alter outflow dynamics (Ferriere, Mac Low, & Zweibel 1991)

Dipole Field Effects on Wind



From ud-Doula & Owocki (2002)

Radio Filament Model



From Yusef-Zadeh (2003).

Latent B Fields from the natal molecular cloud channel Fermi-accelerated electrons up the radio filament.

Conclusions

- Resonant character of nonthermal radio lets it trace particle distribution (but… relativistic tail only)
- Thermal radio is a high-density diagnostic (but… is insensitive to T and oversensitive to clumping)
- Thermal X-ray is a good diagnostic of both density and T for hot gas (but… is also sensitive to clumps)
- Radiative efficiency is a key issue in adiabatic limit
- One-component clumping factor is likely too naive
- Blowouts and leaky shells reduce thermal energy and limit bubble size
- B fields may affect winds close to stars and flows far from cluster, and light up nonthermal filaments

Points to Keep in Mind:

When interpreting diagnostics, consider

- ***What idealized limit is being applied***
- ***Why that limit is applicable***
- ***What are the opposite possibilities***
- ***Which details are lost even as others come more clearly into focus?***

This maintains closer contact with the physics