Radio Stars

D Hogg July 1984

Radio stars - the "original" radio sources, but studied in detail over the last ten years
- need high resolution, good sensitivity, and good positional accuracy. You really have to do this work with arrays - Westerbork, VLA

What kind of emission might be expected?

Flux density $S = \frac{2kT}{\lambda^2}\Omega = \frac{2kT}{\lambda^2}\left(\pi \frac{R_*^2}{D^2}\right)$

For typical values $S = 1$ mJy, $D = 500$ pc, $\lambda = 6$ cm

$$R^2 T = 1 \times 10^{29} \text{ mks}$$

If thermal $T \sim 10^4$ K $R \sim 3\times10^{12}$ m $\sim 4500 R_\odot$

If "stellar" $R \sim 7\times10^8$ m $\sim 1 R_\odot$ $T \sim 2\times10^{11}$ K

Where can we find sources like these?

Thermal - requires an extended region around the star. Look at stars with winds, or stars showing evidence of mass loss.
- O-stars, Wolf-Rayet stars, M supergiants, novae, symbiotic stars, proto-planetary nebulae.

NonThermal - requires in general magnetic fields and some mechanism for accelerating particles
- by observation have found that interacting binaries and x-ray binaries are often radio sources. Only a few single main sequence stars are sources (chromosphere?).

Thermal Emission - thermal bremsstrahlung

The absorption coefficient κ for density N, temperature T and frequency ν is

$$\kappa = 0.212\, N^2\, T^{-1.35}\, \nu^{-2.1} \quad \text{cgs}$$

In general the intensity of the emission from a path along the line of sight through the source is

$$I(\nu, T) = \int_0^{\tau_{max}} B(\nu, T)\, e^{-\tau}\, d\tau$$

with the optical depth $\tau = \int \kappa(\nu, T)\, dl$

At radio wavelengths $\frac{h\nu}{kT} \ll \quad B_\nu = \frac{2kT}{\lambda^2}$

If the temperature in the nebula is constant at T_e, then the brightness temperature T_b is simply

$$T_b = T_e\,(1 - e^{-\tau})$$

The flux density for a source with solid angle Ω

$$S = \frac{2kT_e}{\lambda^2}\,(1 - e^{-\tau})\,\Omega$$

For small optical depths $\tau \ll 1$ $\quad S \propto \nu^2 \kappa T_e \propto T^{-0.35}\, \nu^{-0.1}$

For large optical depths $\tau \gg 1$ $\quad S \propto \nu^{+2}$

For stellar wind sources, an intermediate case: $S \propto \nu^{+0.6}$

Thermal Emission from Stellar Winds

Basic Theory Wright and Barlow 1975 MNRAS 170, 41
Resolution of Winds White and Becker 1982 ApJ 262, 657
Mass Loss Rates Abbott, Bieging, Churchwell 1981 ApJ 250, 645
Nonthermal O Stars Abbott, Bieging, Churchwell 1984 ApJ 280, 671

Stellar winds are now an important part of the study of stellar evolution, and of the interaction of stars with their surroundings. It is important to get estimates of the physical conditions in stellar winds. For a number of reasons it is difficult to make good models of either optical or infrared observations. In contrast, radio observations offer a straight-forward method.

From Wright and Barlow, the radio flux density is

$$S_\nu = 122\left(\frac{\dot{M}}{v_\infty}\right)^{4/3} T^{0.1}\, D^{-2}\, \nu^{0.6} \quad \mathrm{Jy}$$

with $\dot{M}$ in $M_\odot\,\mathrm{yr}^{-1}$, T in K, D in kpc, v_∞ in $\mathrm{km\,s}^{-1}$ and ν in Hz

Surveys have now been made of the early stars within 2.5 kpc. The results are

1. About 50 objects are detected. For O stars there is a relationship between optical luminosity and rate of mass loss. For Wolf-Rayet stars the mass loss rates are much greater than expected from optical luminosity. [Figure 1]

2. Radio data on resolved objects (P Cygni, γ^2 Velorum) confirm basic theory. The visibility curve for γ^2 Vel matches the theory nicely [Figure 2]

3. Stellar winds of early stars may dominate in local regions of the interstellar medium. The nebula NGC 6888 is a wind-blown bubble. [Figure 3]

From Treffers and Chu 1982 ApJ 254, 569 get distance 1.2 kpc, nebular mass 5 $M_\odot$, nebular expansion 75 km/s, and age 2-3 $\times 10^4$ yrs

Stellar winds may also be important in enrichment of ISM. Supernova dominate overall energy

4. But watch out! Perhaps 1/4 of O-stars are non Thermal. High energy particles accelerated in shocks in the outer wind?

Other Types of Stellar Wind Sources

1. M Supergiants α Orionis, α Sco
For α Sco see Hjellming and Newell ApJ 275, 704, 1983
M1.5 Iab + B2.5V [Figure 4] [Figure 5]

Double radio source - emission around M-star is unresolved ($\sim 0.5\,\nu$ mJy) and comes from stellar wind. Emission around B star is extended ($8\,\nu^{0.1}$ mJy) and arises from region where B star "lights up" wind of M star

Results ① M star loses mass at $5\times10^{-6}\ M_\odot\ yr^{-1}$
② Measure production of uv photons
③ Look for other objects over a range of separation - 6 found

2 Interacting Binary Stars

See important review V. Trimble 1983 Nature 303, 137

a) Symbiotic Stars

General IAU Colloquium No. 70 on Symbiotic Stars 1982

Radio Model Taylor and Seaquist Preprint 1984

The term was coined many years ago to describe an optical spectrum that shows both high excitation lines (He II, [Fe VII]) and cool giant features (eg TiO). The objects are now studied over a wide range of wavelengths

x-ray : little, presumably because of dense circumstellar shell

uv : some evidence for a continuum at 10^5 K

optical : some systems definitely binary, periods of hundreds of days. Eclipses, gas streams.

IR : two classes i M, where M star dominates
ii D, where dust emission dominates

radio : of the ~ 100 objects studied, about 25 found, mainly of D-type

Objects not yet resolved, but should be soon. Spectrum of H1-36 consistent with ionized cavity model Mass loss rate (4×10^{-5}) very high

b) Transition Objects V1016 Cyg, HM SGE, RR TEL

Example HM SGE Kwok, Bignell, Purton 1984 ApJ 274, 188

The star brightened from $16^m - 12^m$ in six months in 1975, and has stayed bright since then. The optical-IR shows molecular absorption bands (CO, H_2O) and variability - Mira M supergiant. The ultraviolet shows many high excitation lines with ionization potential greater than 100 eV - suggestive of a hot compact white dwarf of temperature 10^5 K.

Again radio emission consistent with expanding ionized cavity.

c) Novae

Radio Properties   Hjellming et al 1979 AJ 84, 1619
Example of Theory   Kwok 1983 MN 202, 1149

Novae are well known objects which 1) brighten by ~ 9 magnitudes in a few days; 2) decays in a period of years, though by 2-5 magnitudes in the first 50 days; shows ejection of matter with velocities in the range 1000 - 2000 Km s^{-1} They may result from the transfer of matter from a main sequence or giant star to a compact companion.

Radio emission is well-behaved. The data are fitted by a model with large density and velocity gradients; with time the mass ejected evolves from an optically thick disk to a completely thin shell.
Mass loss ~ 2×10^{-4}, velocities 200, 5000 km s^{-1}

New feature   Reynolds and Chevalier 1984 ApJ 281, L33

They have detected nonthermal emission from the shell of the nova in Perseus 1901. The significance is that the particles must have been accelerated by the expansion of the shell. The energy involved is so great that they could not have merely been swept up.

Input of particles to the interstellar medium is still less than that of supernovae.

3. Bipolar Flows - Young Objects

a) There is an extensive literature on This subject, mostly involved with line obsewations. As an example of The continuum work That can be done see Felli et al 1984 preprint on S106.

In This case The central mass-losing object can be seen at radio wavelengThs [Figure 6]

Mass loss rate deduced $\sim 2 \times 10^{-6}$ M⊙ yr^{-1}, typical of a B0 to O9 Star

b) T Tauri objects
See for example Cohen, Bieging, Schwartz 1982 ApJ 253, 70

These are Thought to be recently formed stars and are often found associated with nebulosity or molecular clouds. Several lines of evidence suggest That They are losing matter in winds.
At least 6 are now known to be radio sources. The detection of These is important because it demonstrates That They are indeed losing matter in a constant velocity wind, at rates between 3×10^{-7} and 3×10^{-5} M⊙ yr^{-1}.

Non Thermal Stellar Sources

I The R S CVn binary stars
About 24 known as radio sources
Examples HR 1099 UX ARI

Reference Linsky 1984 3rd Cambridge Workshop on Cool Stars (Preprint)

Defining characteristics
1 Binaries, orbital periods 1-20 days
Rapid rotation, tidally synchronized

2 Strong Ca II lines - indicates non-radiative heating

3 The hotter star is F or G. The companion is a cooler less evolved star

4 Optical light curve is distorted. The distortions are caused by star spots, cool with magnetic fields up to 1000 gauss

5 Mass ratios one, but detached binaries.

Radio properties
Characterized by flares, of duration a few days
Highly polarized. Sometimes the variation in flux is in one hand of circular polarization only. [up to 40% circular]
Probably gyrosynchrotron emission

HR1099 d ~ 30 pc peak flux 1 Jy

II Energetic binary systems

a) Counterparts of X-ray sources

Interesting objects, but progress in understanding the radio emission has been slow

Sco X-1 the first. A radio triple, with very little apparent expansion
Cyg X-1 P 5.6 days O9 Iab + black hole?
Cyg X-3 The strongest, reaching 20 Jy at radio wavelengths

Some recent work on Cyg X-3 Geldzahler et al 1983 ApJ 273 L65

Implied expansion velocity > 0.7c
Possible model (Vestrand) Young pulsar in close binary system. Matter from companion envelopes the binary. γ-rays from pulsar interacting with extended envelope produces quiescent radio emission (synchrotron)

b) SS433 - a real winner, with lots of good results

Reference Margon 1984 Ann Rev Astron Astrophys (in press) (preprint)

Found in a survey of emission line objects, it was also noted as an X-ray and radio source. The real excitement occurred in 1979, when velocities of order 50000 km s^{-1} were identified in the spectrum.

The following picture has been developed [Figure 7]
It is a binary star with an OB primary and a compact secondary. Gas is flowing from the primary to form an accretion disk around the secondary. The period of the binary is 13 days. The accretion disk contributes a lot of light in the visible, so that the binary orbit is poorly determined.

The high velocities are believed to arise in a twin jet, the axis of which rotates with a period of 164 days. The central axis of the rotation cone is inclined by 79° from the line of sight and the half angle of the cone is 20°. The velocity of material in the jets is 0.26c, and creates a large second order Doppler shift of 12000 km s^{-1}, appearing as an offset in the velocity.

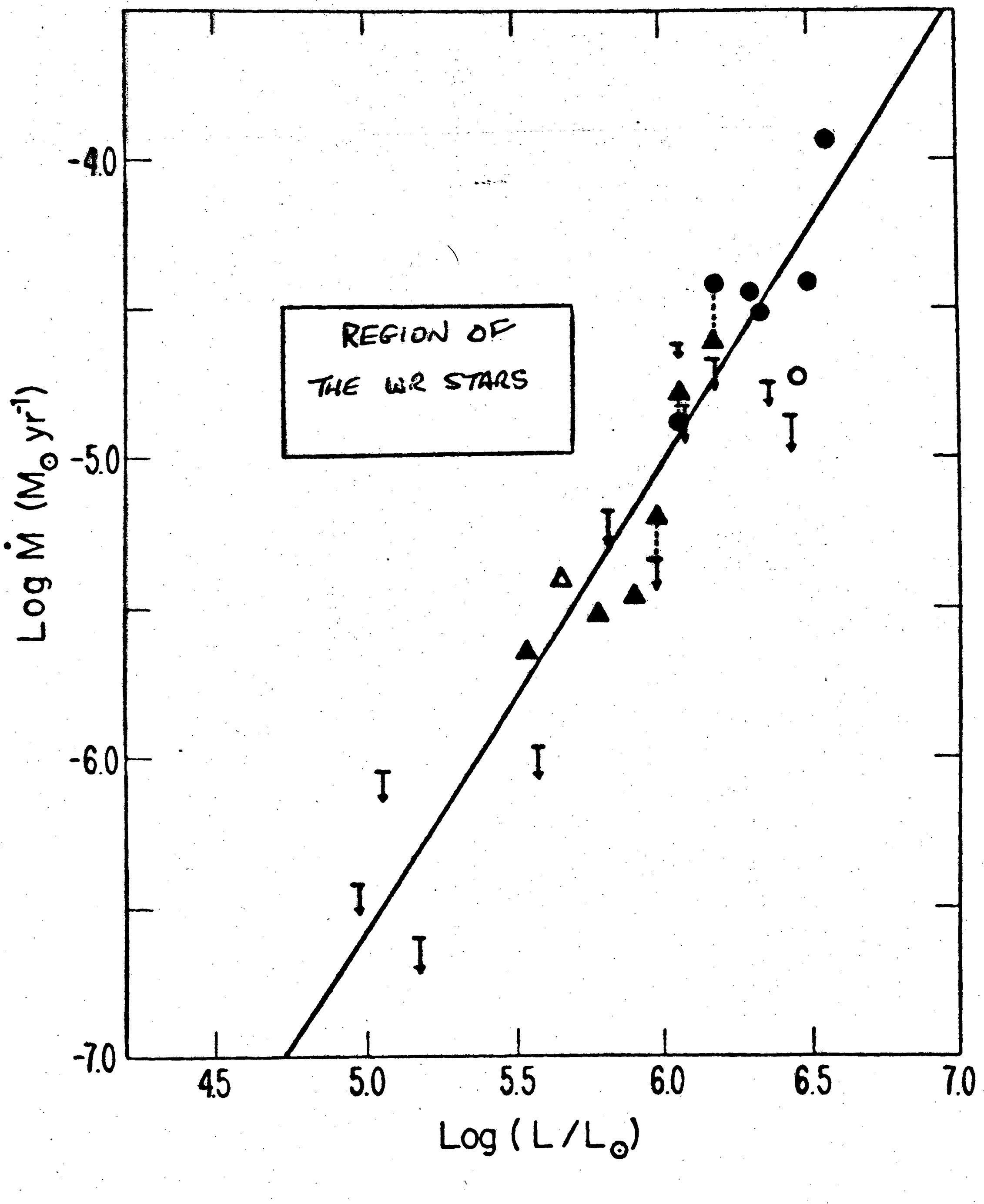
This picture was one of several models advanced on the basis of the early optical data. The radio data was consistent with this picture [Figure 8] an indeed helped sort out some of the ambiguities in the geometry.

Specific radio results:
Distance 5 kpc
Left hand side coming toward us, rotation clockwise

Current work
Look for slow down
Develop theory of jets. Is matter being entrained?
(Radio pattern more stable than optical pattern)

III Flare Stars
Examples UV Cet, YY GEM, AM HERC
Often binary, showing quiescent radio emission
The flares can be rapid - seconds or less, and can be highly polarized

Current thinking - quiescent emission is gyrosynchrotron (characteristic T 10^8, B 200 gauss) while the flaring is by an electron-cyclotron maser

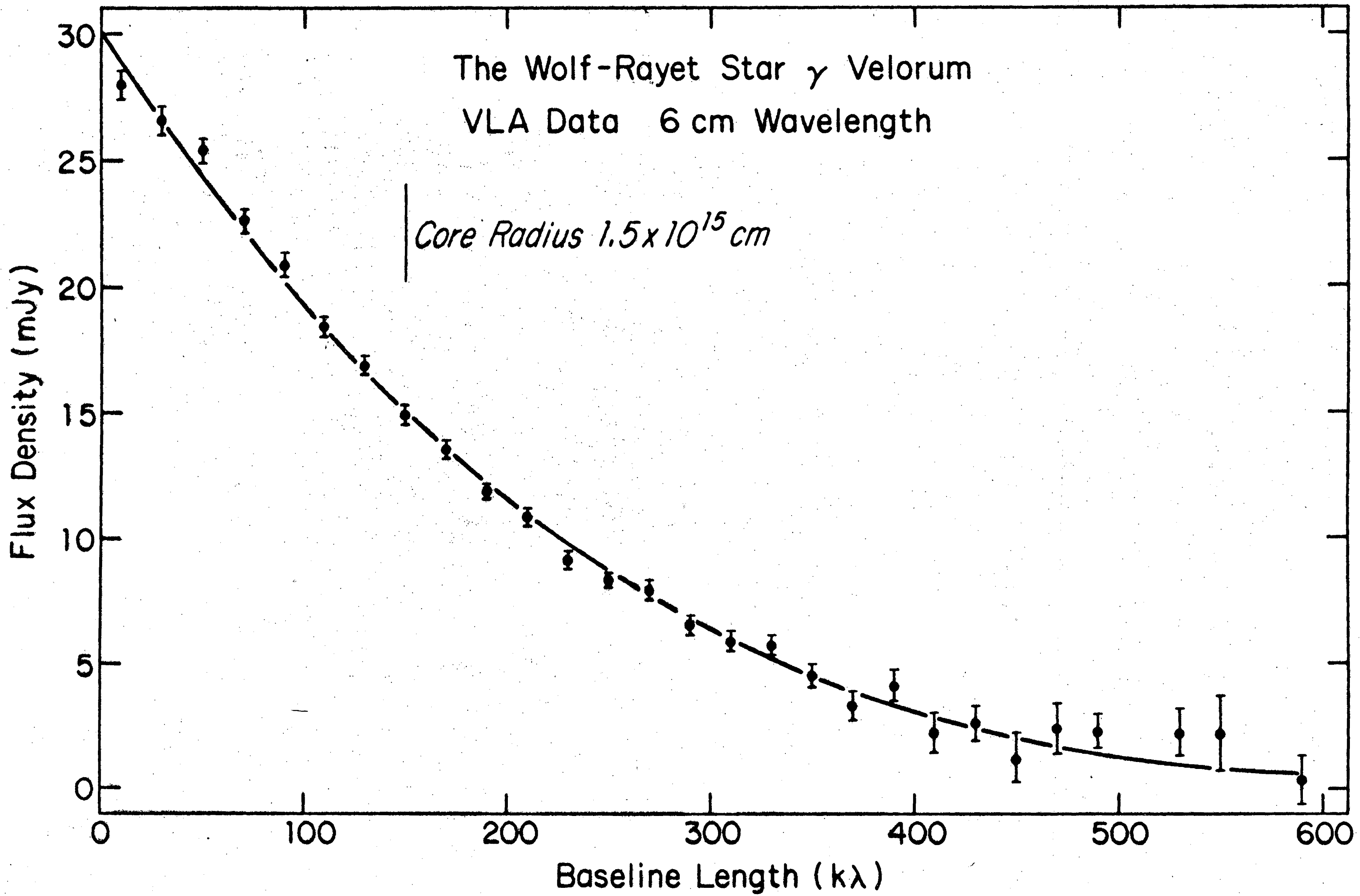


~~Figure 4a~~

ABBOTT

FIGURE 1

FIGURE 2



— HOGG

right ascension and declination respectively. The contours were corrected for a slight decrease of trans-

and Episov (1968) and Lozinskaya (1970) to divide
nebula into regions of approximately constant intens
ratio $[\mathrm{N\,II}]/\mathrm{H}_\alpha$. The numbers give the factor I(H

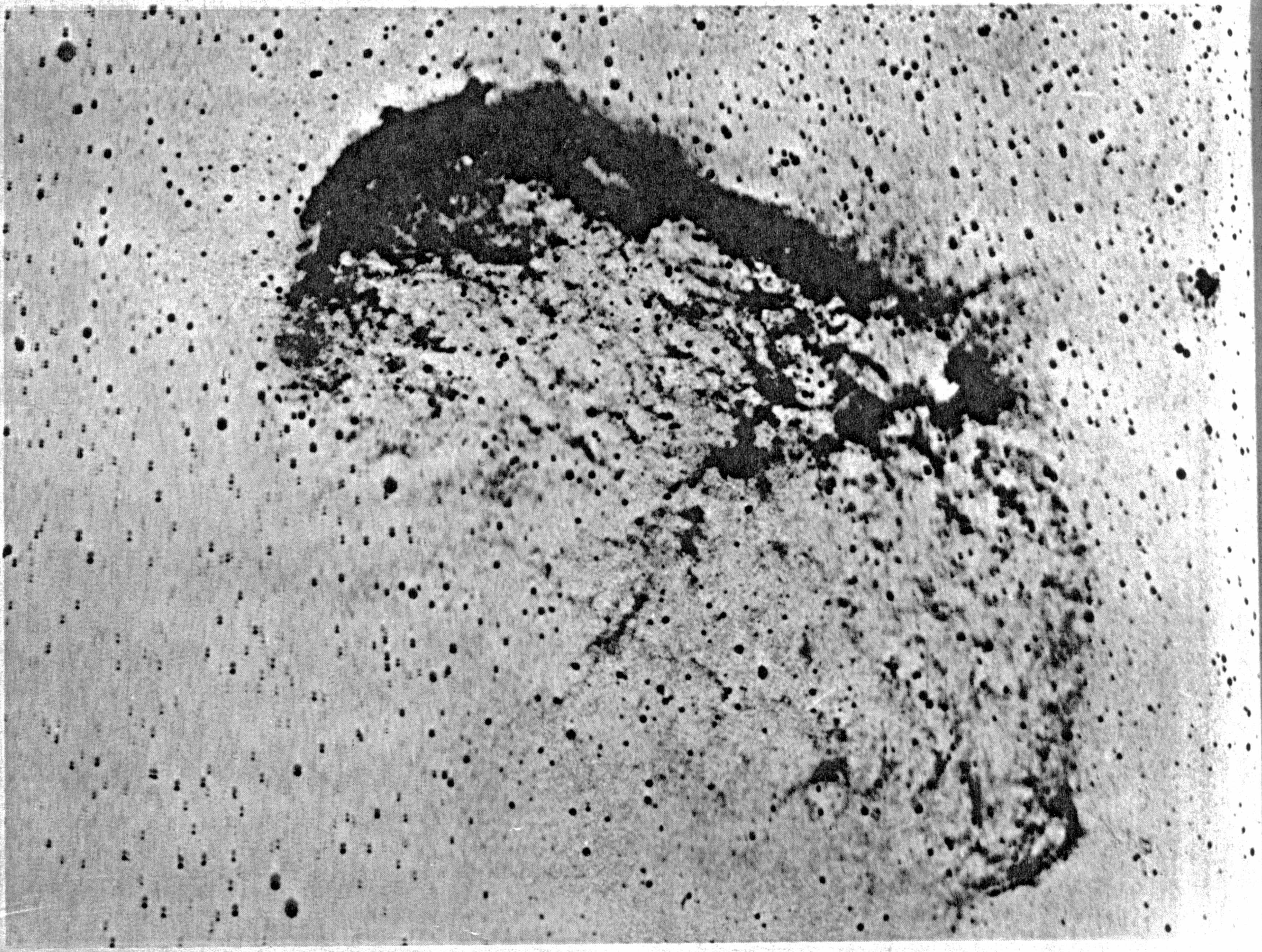
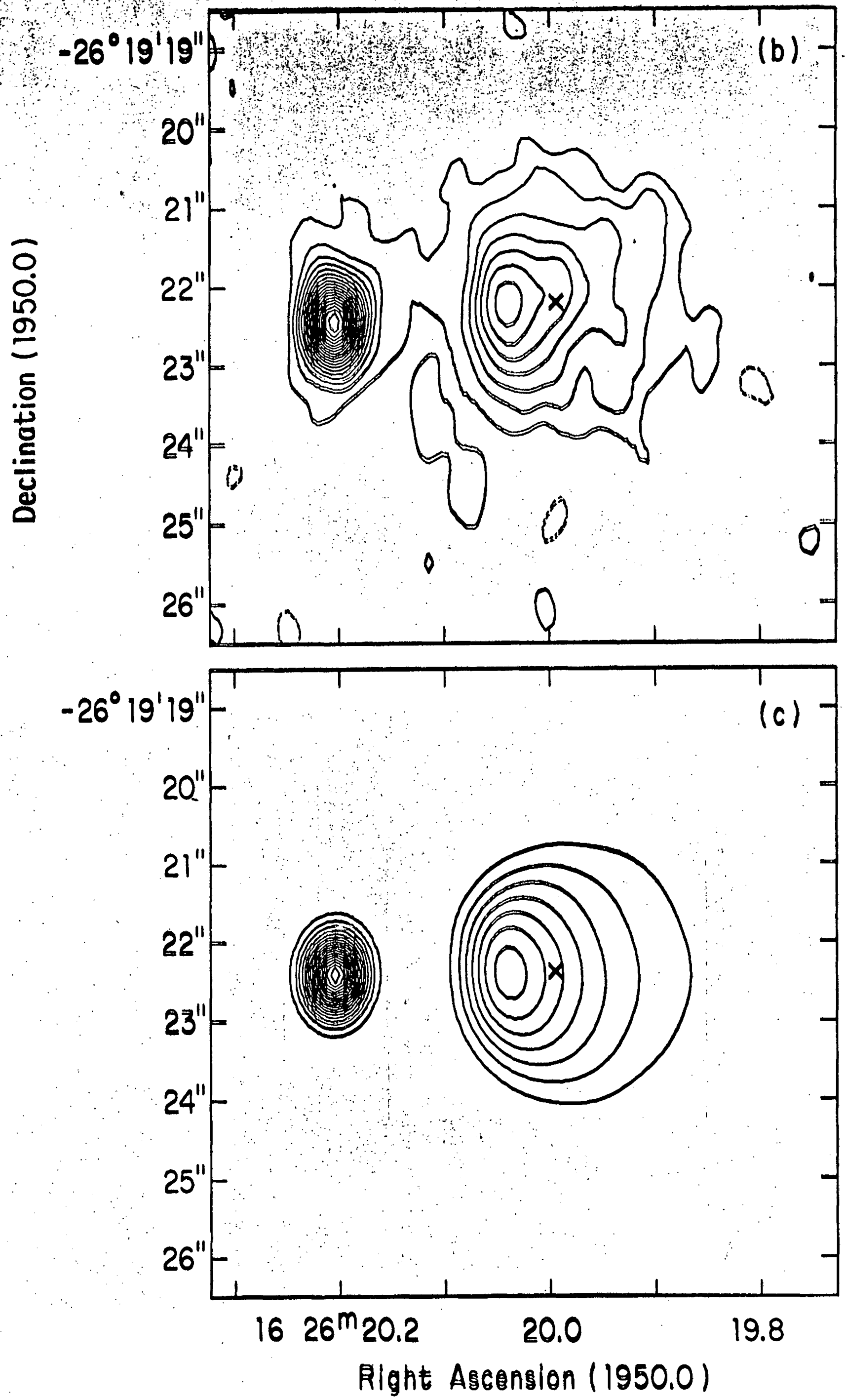


Fig. 1. Photograph of NGC 6888 in $H_\alpha+[\mathrm{N\,II}]$. See Text. Taken with the Hale Observatories 48" Schmidt-telescope

FIGURE 4



HJELLMING + NEWELL

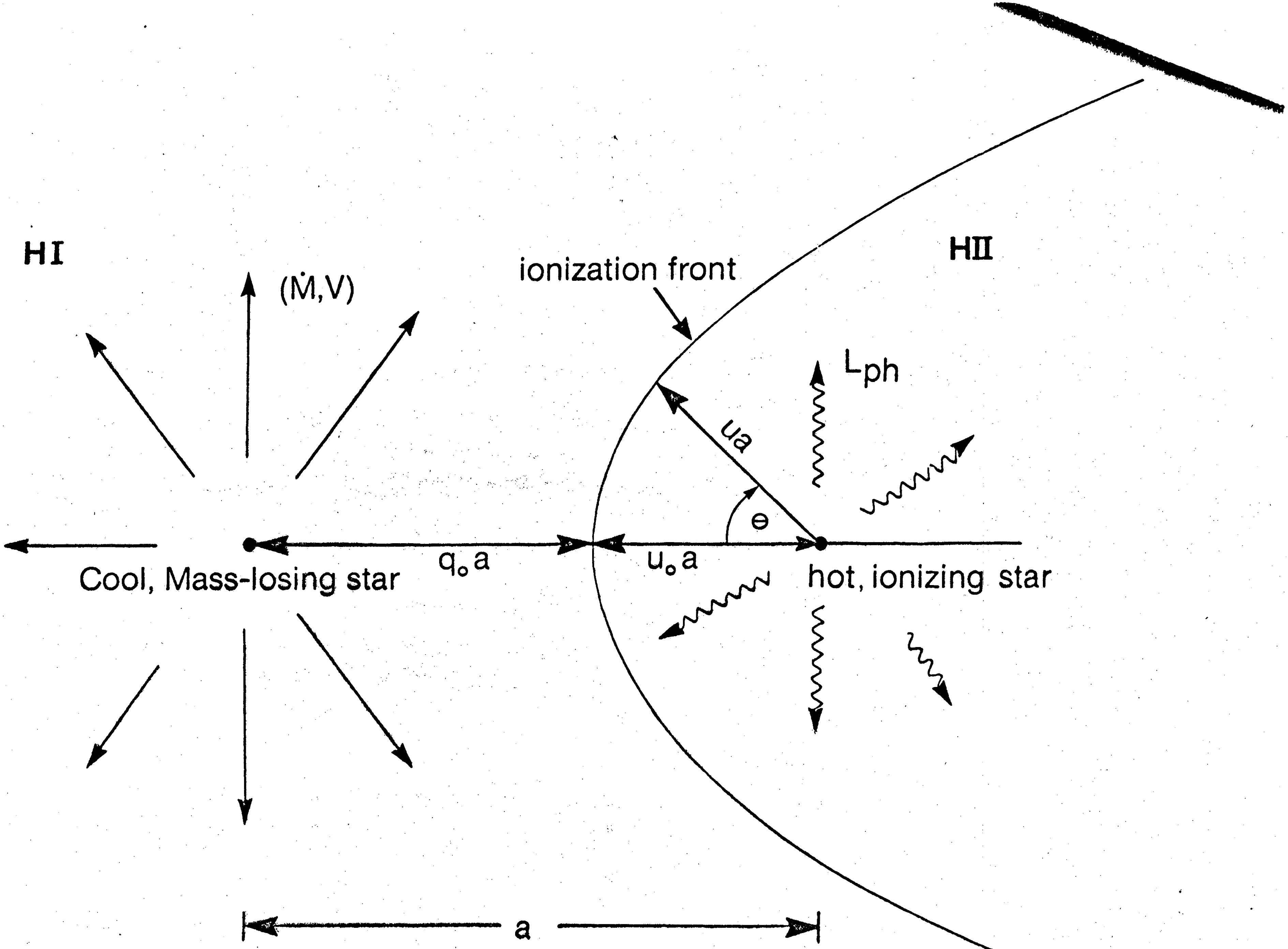
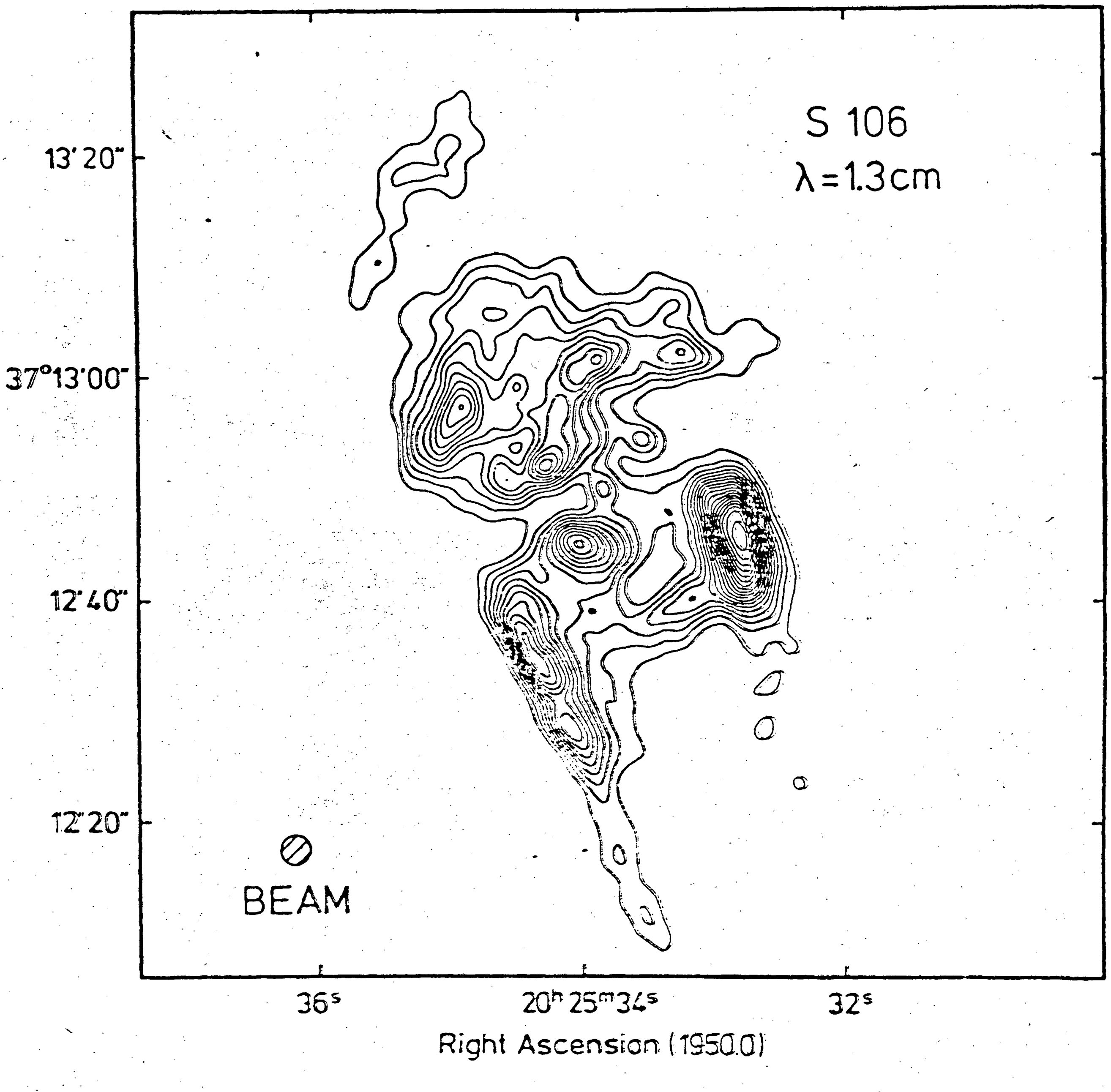


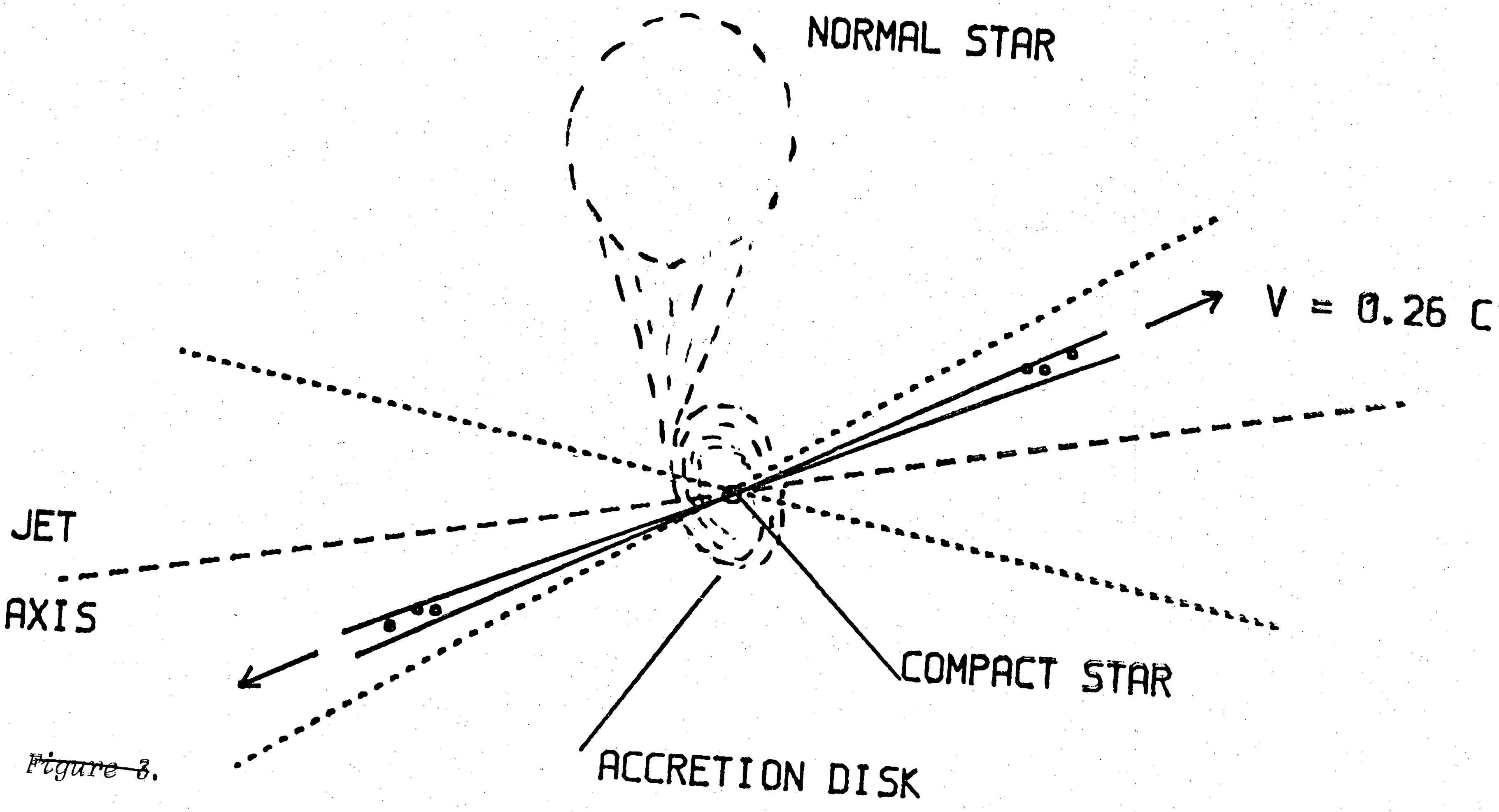
FIGURE 5

TAYLOR-SEAQUIST



~~Fig. 1~~

FIGURE 6 FELLI ET AL

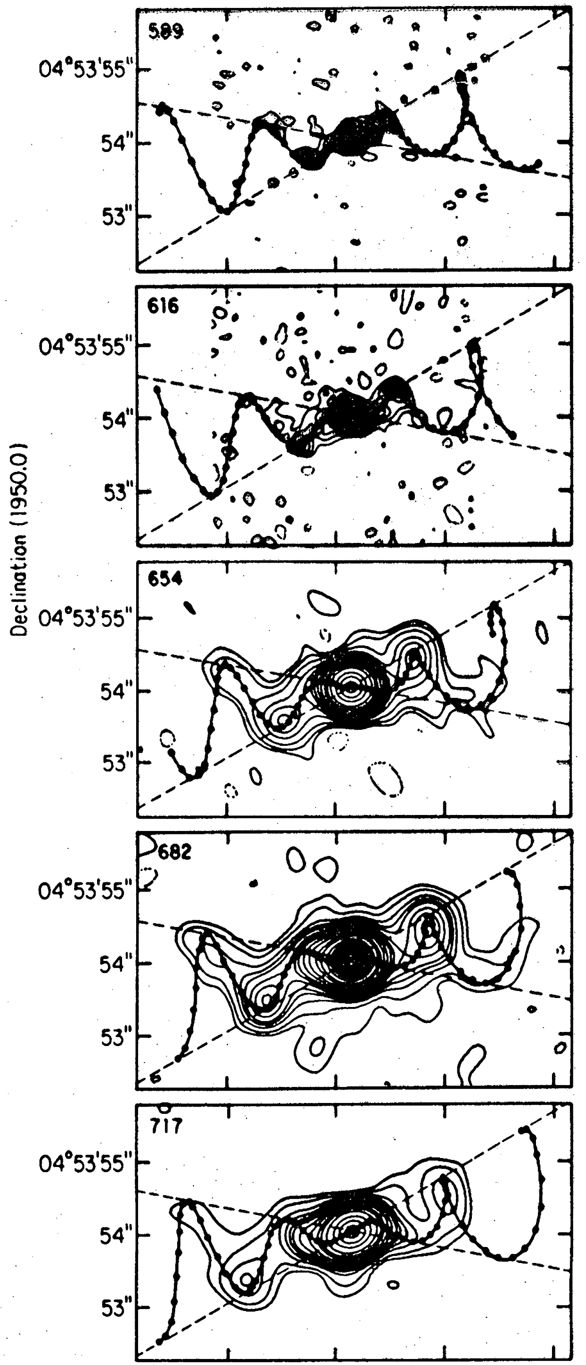


~~Figure 3~~.

FIGURE 7

HJELLMING

FIGURE 8



HJELLMING + JOHNSTON