STARBURST-DRIVEN GALACTIC WINDS

INTRODUCTION

- The physics of starburst-driven winds
- Observational Consequences

DEMOGRAPHICS

- At Low Redshift
- At High Redshift

OUTFLOW RATES

- X-ray Constraints
- Optical Line Emission
- Absorption-Line Constraints

LONG-TERM FATE

- Radiative Cooling
- How Far Do Winds Travel?
- Mass and Phase Dependence

PHYSICS OF STARBURST-DRIVEN WINDS

DYNAMICAL EVOLUTION

- Kinetic energy supplied by supernovae and stellar winds ($\dot{E} \sim 10^{-2}\ L_{bol} \sim 10^{-1}\ L_{ion}$)
- Supernova rate per unit volume high: 2 to 4 orders-of-magnitude higher in starbursts than than in normal galaxies
- Porosity of starburst ISM high
  Radiative losses small
  Supernovae KE is efficiently thermalized
- Expect that young outflows will resemble classic stellar wind-blown bubbles
- Hot gas will expand most rapidly along direction of steepest pressure gradient
- Superbubble propagates out of disk, accelerates, fragments, and vents hot gas into the halo (“blow-out”)
- Result: Weakly-collimated bipolar wind propagating through halo

BASIC PROPERTIES

- $\Lambda = \dot{M}_{wind}/\dot{M}_{sne}$ **“mass-loading”**
  $\epsilon = \dot{E}_{wind}/\dot{E}_{sne}$ **heating efficiency**
- **Temperature of hot gas:**
  $\mathrm{T} = 0.4(\dot{E}/\dot{M})(\mu m_p/k) \sim 10^8\ \epsilon/\Lambda\ \mathrm{K}$
- **Metallicity of hot gas:**
  $Z_\alpha \sim [8 + (\Lambda - 1)Z_{\alpha,ism}]/\Lambda$
  $Z_\alpha/Z_{Fe} \sim [8 + (\Lambda - 1)Z_{\alpha,ism}]/[0.2 + (\Lambda - 1)Z_{Fe,ism}]$
- **Wind ram pressure:**
  $\mathrm{P(r)} = \dot{M}v/r^2\Omega_W$
  $\mathrm{P/k} = 6 \times 10^6\ \dot{p}_{35}\ r_{kpc}^{-2}\ (4\pi/\Omega_W)\ \mathrm{K\ cm^{-3}}$
- $\mathbf{P}_{ram}/\mathbf{P}_{rad}$:
  $\sim 3(\Lambda\ \epsilon)^{1/2}(4\pi/\Omega_W)$
- **During superbubble phase:**
  $v_{shell} = 0.46(\dot{E}/t^2\rho)^{1/5} \sim \mathrm{a\ few\ hundred\ km/s}$
- **Post-blow-out velocity of hot wind:**
  $\mathrm{v}_{hot} = \sqrt{2\dot{E}/\dot{M}} \sim 3000\ (\epsilon/\Lambda)^{1/2}\ \mathrm{km/s}$
- **Clouds in wind accelerated to:**
  $v_{term} \sim 560\ [\dot{p}_{35}/(\Omega_W/4\pi)\ r_{kpc}\ N_{21})]^{1/2}\ \mathrm{km/s}$
- **Note different kinematics of wind and clouds!**

OBSERVATIONAL CONSEQUENCES

A MULTIPHASE FLOW

- **The X-ray emission traces the interaction of the wind fluid with ambient disk/halo gas**
- **Close morphological association between X-rays and Hα emission**
- **Typical α/Fe ratio $\sim$ 3 × solar**
- **X-rays from wind shock?**
  Implied $\mathrm{v}_{wind} \sim$ 600 to 800 km/s
- **Consistent with significant mass-loading:**
  Implied Λ of-order 10
- **Optical line emission from shocked and/or photoionized entrained ISM**
- **Blueshifted interstellar absorption-lines from entrained/accelerated gas spanning wide range in ionization state**
- **Correlation between outflowing cool gas and dust: the outflows are highly dusty**
- **Nonthermal radio emission from cosmic ray electrons and B-field advected in the hot wind fluid**

DEMOGRAPHICS

Optical emission-line survey of edge-on starbursts

- Incidence rate of shock-heated/-accelerated extraplanar ionized gas reaches ~ 100% for powerful high-intensity starbursts
- Threshold for outflow: $\Sigma_{SFR} \geq 10^{-1}\ M_{\odot}\ yr^{-1}\ kpc^{-2}$

X-ray survey of the 22 nearest dwarf starbursts, edge-on L_* starbursts, and ULIRGs

- All show diffuse halos of soft X-ray emission
- L_{halo} and R_{halo} scale with SFR
- Same surface brightness, temperature, enhanced α/Fe ratios
- Same close morphological relation between X-ray and Hα emission

Absorption Line Surveys

- The interstellar absorption lines are generically blue-shifted by a few hundred km/s in powerful starbursts
- Similar results for Lyman Break Galaxies

OUTFLOW RATES

X-Rays

- The X-ray luminosity, temperature, and size yield M F$^{-1/2}$, $\dot{P}$ F$^{1/2}$, and TE F$^{-1/2}$, where "F" is the volume filling factor
- The X-ray size and temperature lead to a "crossing-time" and hence $\dot{M}$ and $\dot{E}$
- For $F \sim 1$, $\dot{E} \sim \dot{E}_{sne}$ and $\dot{M}$ = several times the SFR (Λ of-order 10)
- Note: PΔV $\propto$ F$^{-1/2}$

Optical Emission Lines

- Measure mass directly (measure n_e) and can also directly measure outflow velocities
- Measure the wind ram pressure:
  $P(r) = M\ v/r^2\Omega_W$
  $\dot{M}\ v = P(r)\ r^2\ \Omega_W$
- Implied outflow rates in the hot wind fluid:
  $\dot{M} = 20\ (v/10^3)^{-1}\ (\Omega/4\pi)\ (L_{bol}/10^{11})\ M_{\odot}/\text{yr}$
  $\dot{E} = 10^{43}\ (v/10^3)\ (\Omega/4\pi)\ (L_{bol}/10^{11})\ \text{erg/s}$
- $\dot{M}$ is several times the SFR and $\dot{E} \sim \dot{E}_{sne}$

Interstellar Absorption Lines

- Absorption-line strength traces column density (not emission-measure), and so is a "fairer" tracer of mass
- Absorption-lines provide unambiguous kinematic information
- Gas columns are a few × 10^{21} cm^{-2} and outflow speeds are a few hundred km/s
- Outflow rate:
  $10\ (r_*/kpc)\ (N_H/10^{21})\ (\Delta v/100)(\Omega_W/4\pi)\ M_\odot/yr$
- Typical values:
  $\dot{M}$ = a few times the SFR
  $\dot{E} \sim 10\%\ \dot{E}_{sne}$

Summary

- Although the methods above all require uncertain assumptions, they are independent of one another
- Conclusion: the outflows require of-order unit-efficiency for the conversion of supernova KE and carry out mass at a rate of-order the SFR

THE FATE OF WINDS

Are they "quenched" by radiative cooling?

- $L_X \sim 10^{-2}\dot{E}_{sne}$
  Radiative cooling by hot gas insignificant
- FUSE observations of OVI:
  Radiative losses from coronal phase insignificant

How far do winds travel?

- Surface brightness drops like r^{-3} (even ignoring effects of cooling). Tough to trace in emission!
- Wind-Cloud collision in M 82 (wind "lights-up" at large radii)
- Ram-pressure stripping of ISM by wind from NGC 3079?
- Absorption-lines trace column density ($N \propto r^{-1}$)
- Lyman Break Galaxies blow holes in IGM with radii ~150 kpc

Do winds escape?

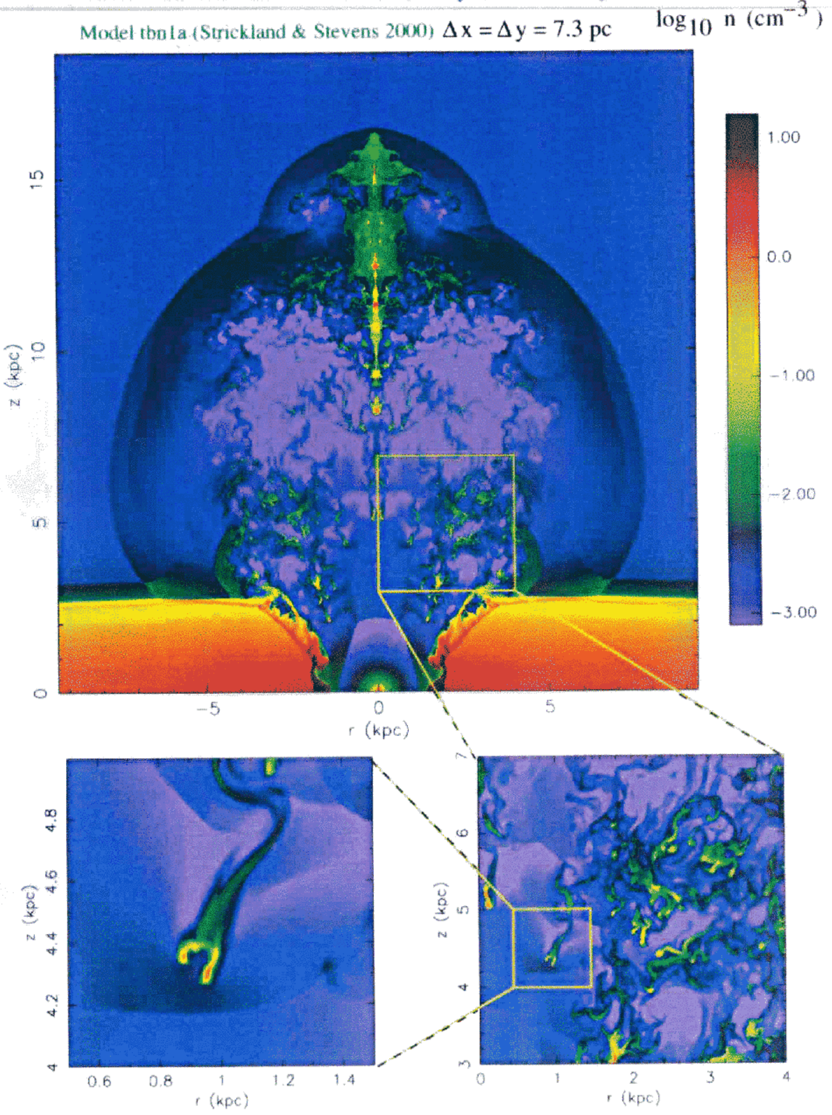
- T_X independent of v_{rot}
- HOT gas can escape from dwarf galaxies but probably not from massive galaxies
- Outflow speeds in cooler gas DO scale with v_{rot}
- "Escapability" is both mass- and phase-dependent
- Selective loss of metals and kinetic energy in wind fluid from low mass galaxies
- Consistent with form of mass-metallicity relation for galaxies

SUMMARY

- Starburst-driven winds are ubiquitous in galaxies with SFR/area exceeding $\sim 0.1\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$
- These winds are complex multiphase phenomena
- The X-ray properties imply that the winds are strongly mass-loaded
- A high efficiency of utilizing supernova energy is required
- The winds carry a mass flux of-order the SFR
- The escapability of the wind is strongly dependent on the gas phase and the galaxy mass

M82–like starburst: number density at t = 17 Myr.

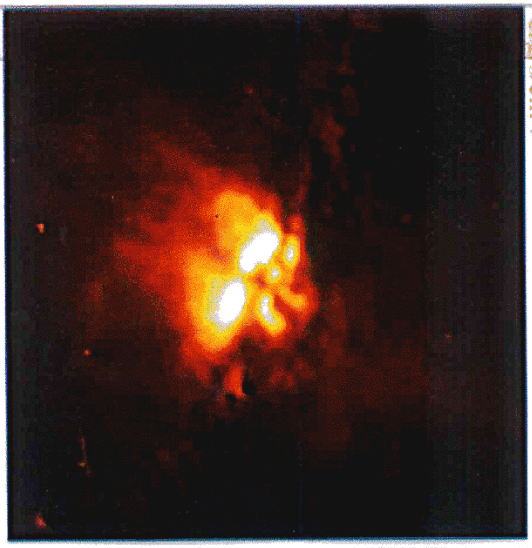
Model tbn1a (Strickland & Stevens 2000) $\Delta x = \Delta y = 7.3$ pc



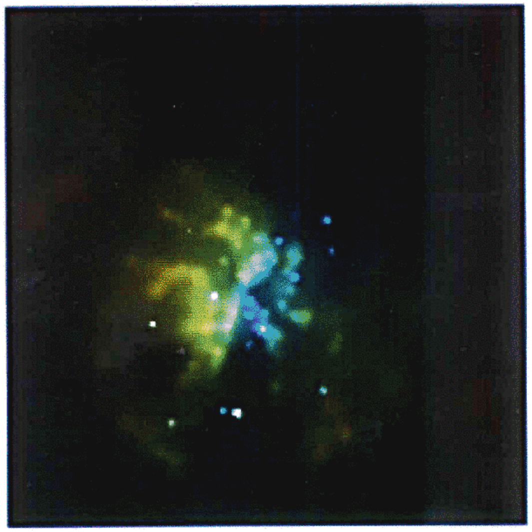
DKS

STRICKLAND ET AL.

Comparing optical emission with X-ray emission: Messier 82



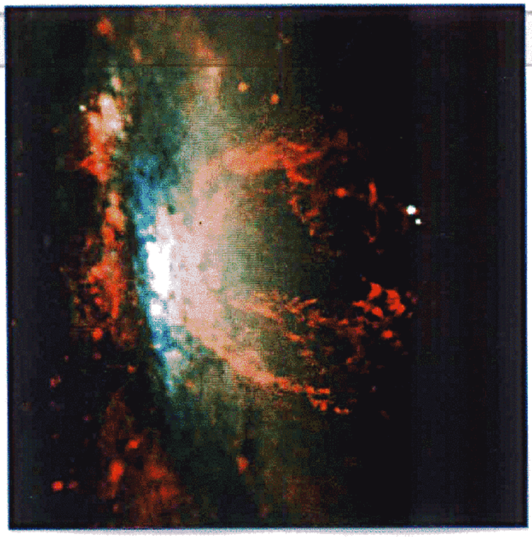
Red: Hα+[NII], ~2 kpc x 2 kpc. (30" FUSE ap. M82-A) $f_{H\alpha} \sim 3.5e\text{-}13$ erg/s/cm^2.



X-ray: red 0.3-1.0 keV, green 1-2 keV, blue 2-8 keV. (30" FUSE ap) $f_X \sim 4.5e\text{-}13$ erg/s/cm^2.

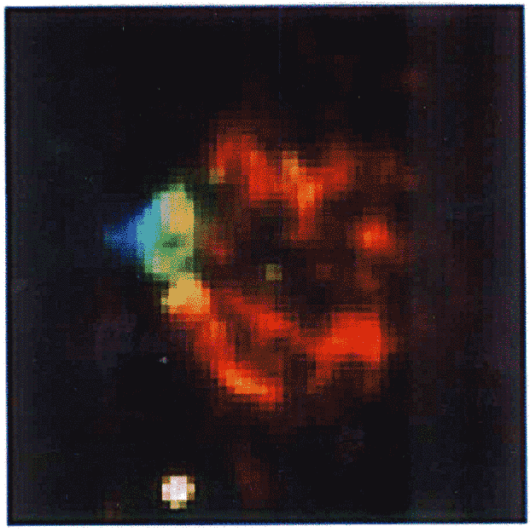
Comparing optical emission with X-ray emission: NGC 3079

Red: Hα+[NII], green: I, ~3 kpc x 3 kpc.
$f_{H\alpha}$ ~ 1e-13 erg/s/cm².

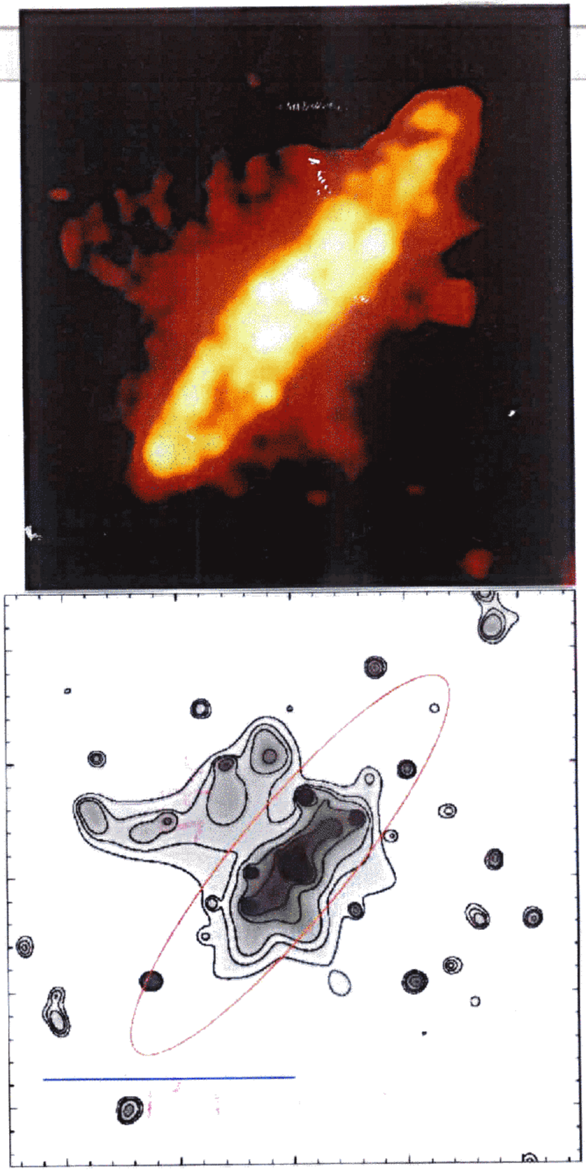


(Cecil et al 2001.)

X-ray: red 0.3-1.0 keV, green 1-2 keV, blue 2-8 keV. f_X ~ 1.6e-13 erg/s/cm².



(Strickland, Heckman & Weaver in prep.)



NGC 253: ROSAT PSPC and Hα

Is the wind/cloud interaction model true even over ~ 10 kpc scales?

STRICKLAND ET AL,

XMM Grating Spectrum of NGC253 wind

Pietsch et al.

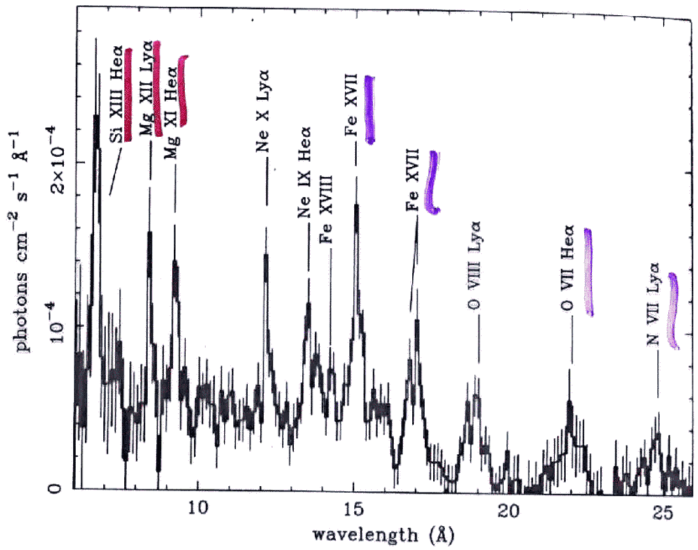


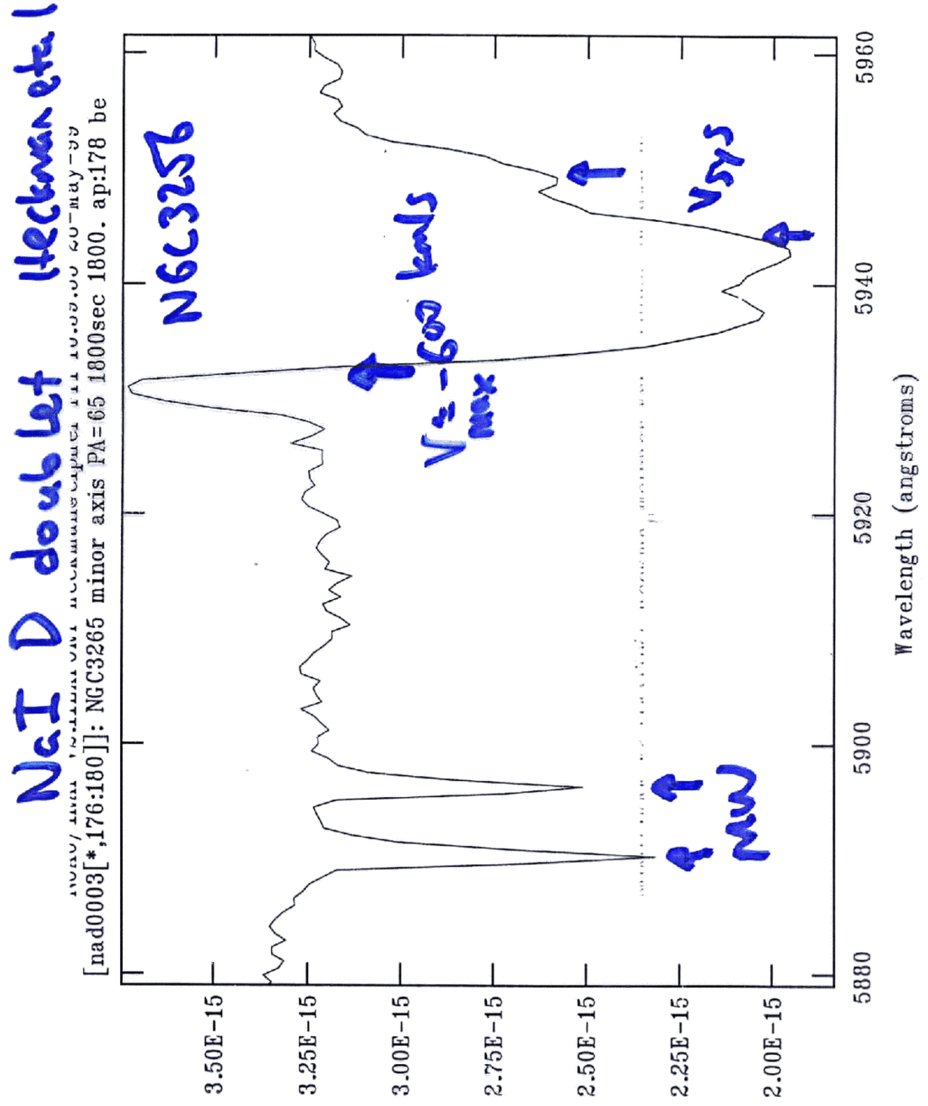
Fig. 5. "Fluxed" RGS spectrum of the bright nuclear area of NGC 253 (extraction region 1′ along the minor disk axis, covering nucleus and plume). Bright emission lines are identified

— gas at kT ≈ 300 eV

— gas at kT ≈ 1.5 keV

NaI D doublet Heckman et al.

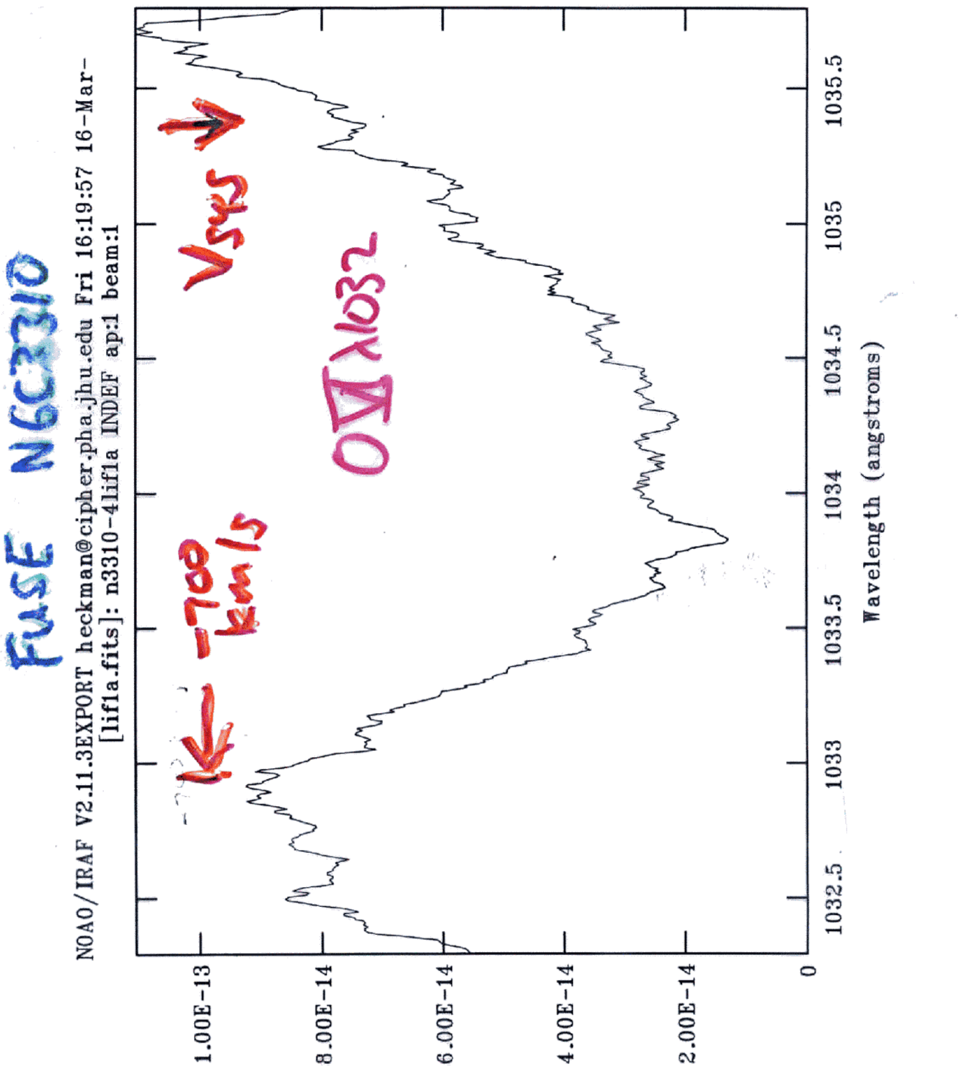
NGC3256



$V_{max} \approx -600$ km/s

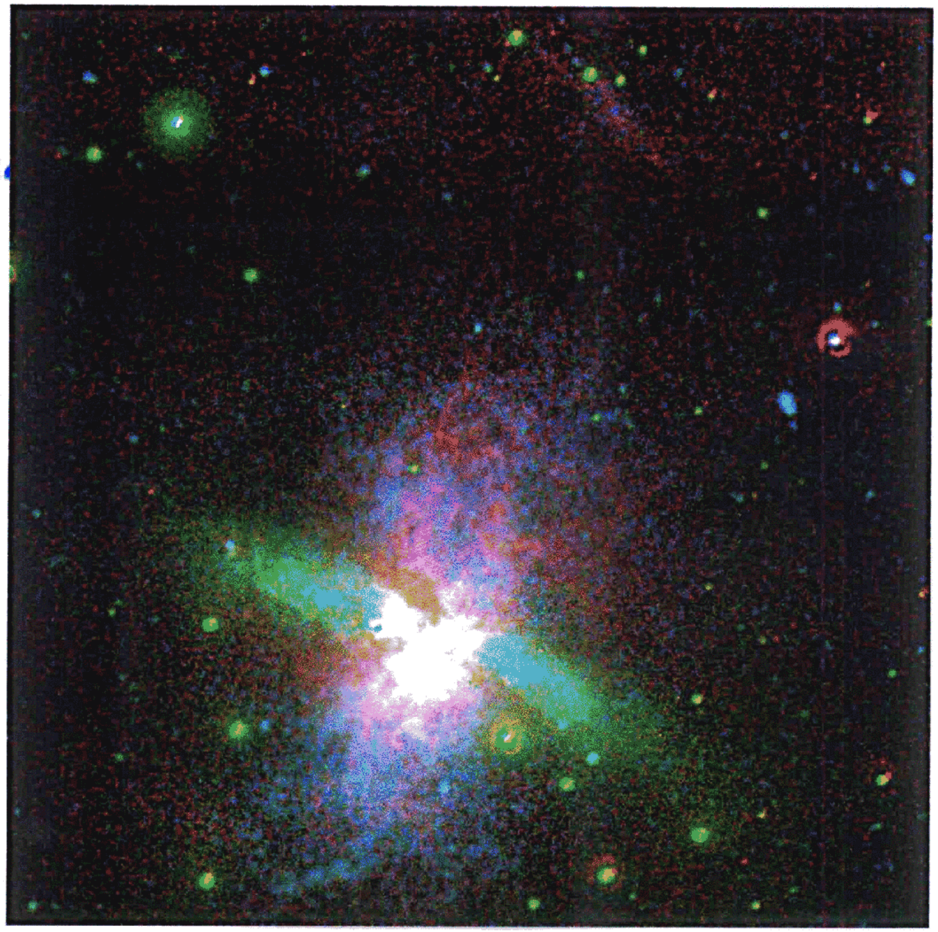
Vsys

MW



M82 Galex UV Blue
Hα Red

Hoopes et al.



M82 Hα + continuum

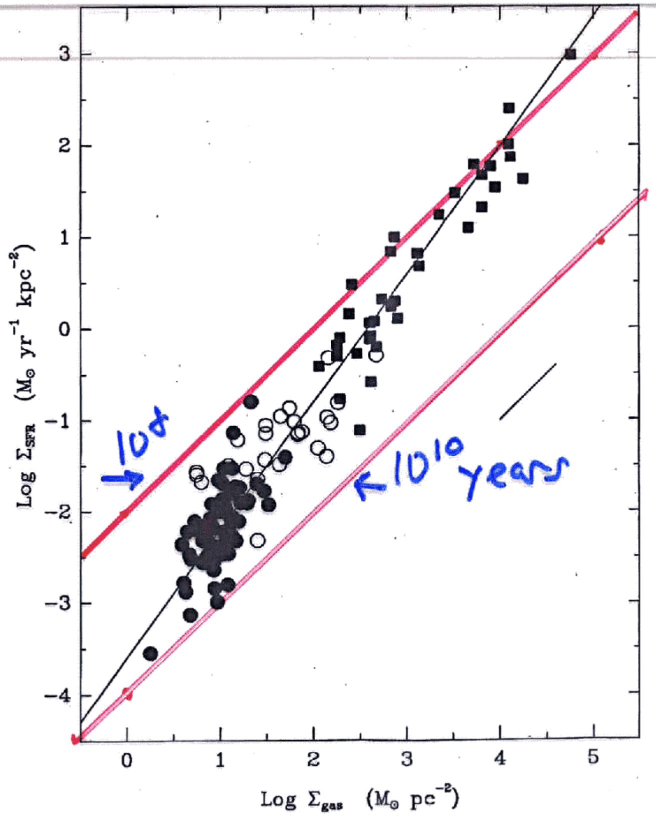
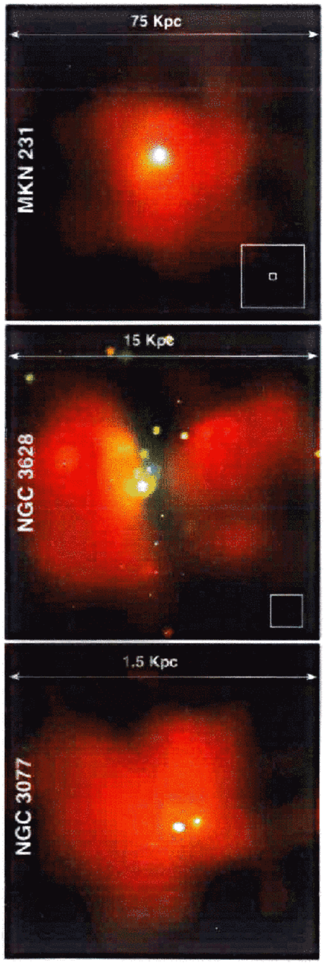
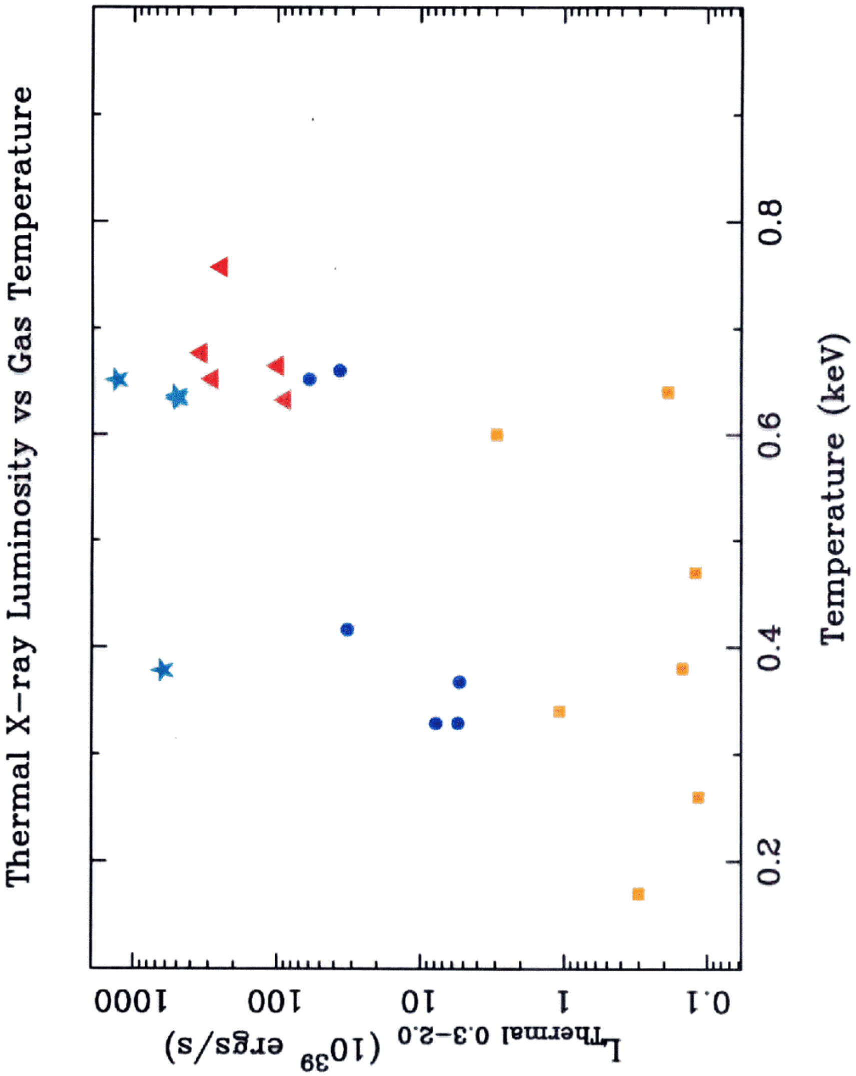
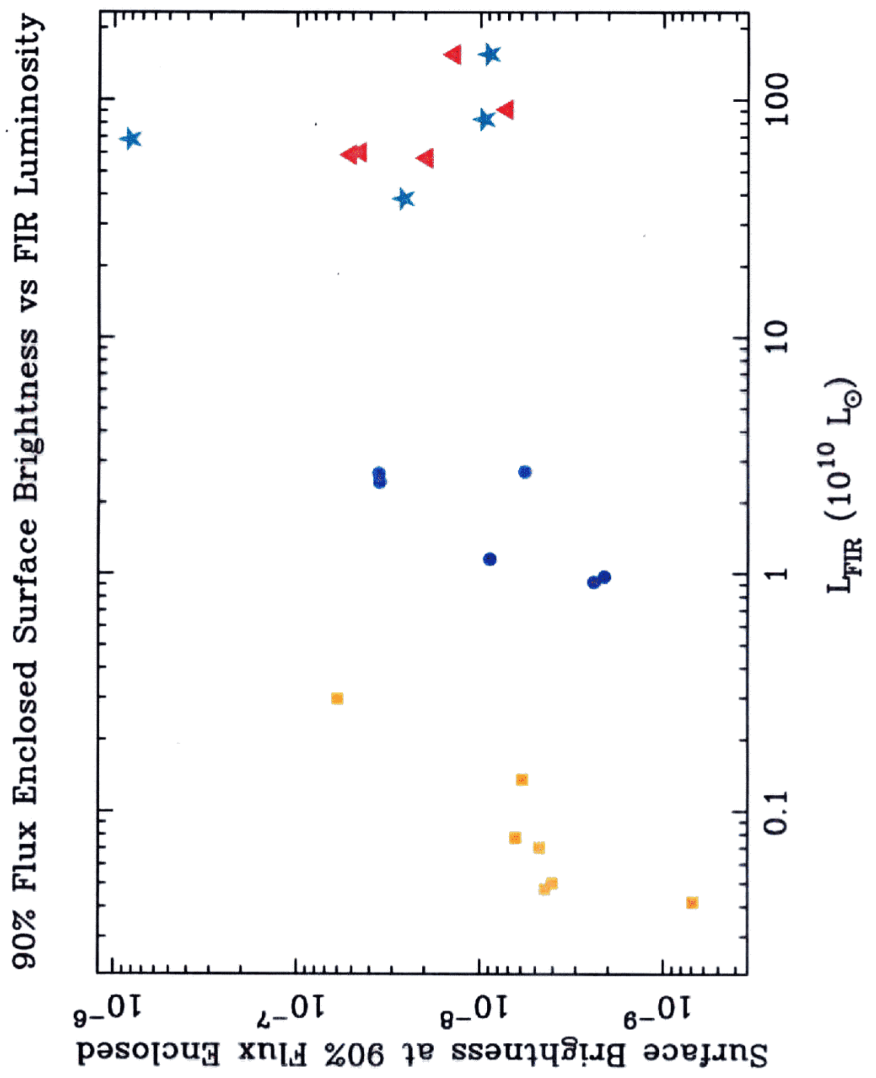


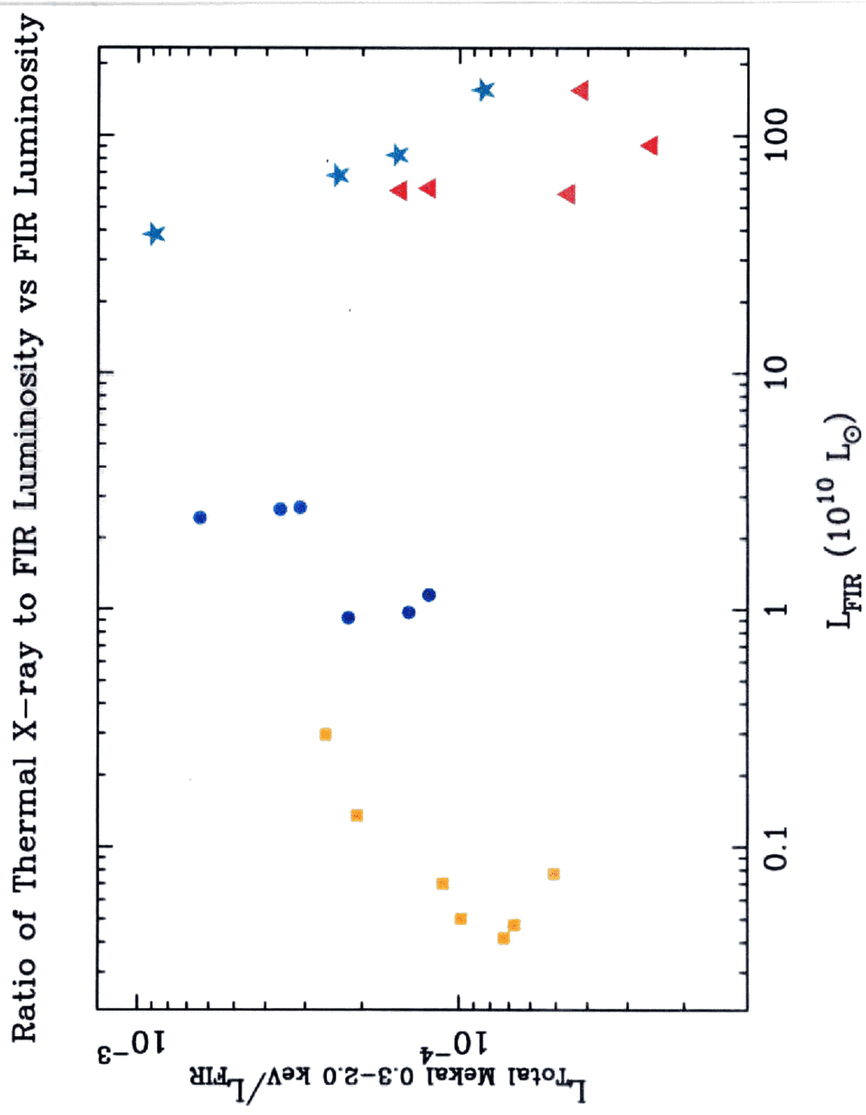
FIG. 6.—Composite star formation law for the normal disk (*filled circles*) and starburst (*squares*) samples. Open circles show the SFRs and gas densities for the centers of the normal disk galaxies. The line is a least-squares fit with index $N = 1.40$. The short, diagonal line shows the effect of changing the scaling radius by a factor of 2.

Kennicutt


75 Kpc
MKN 231
15 Kpc
NGC 3628
1.5 Kpc
NGC 3077

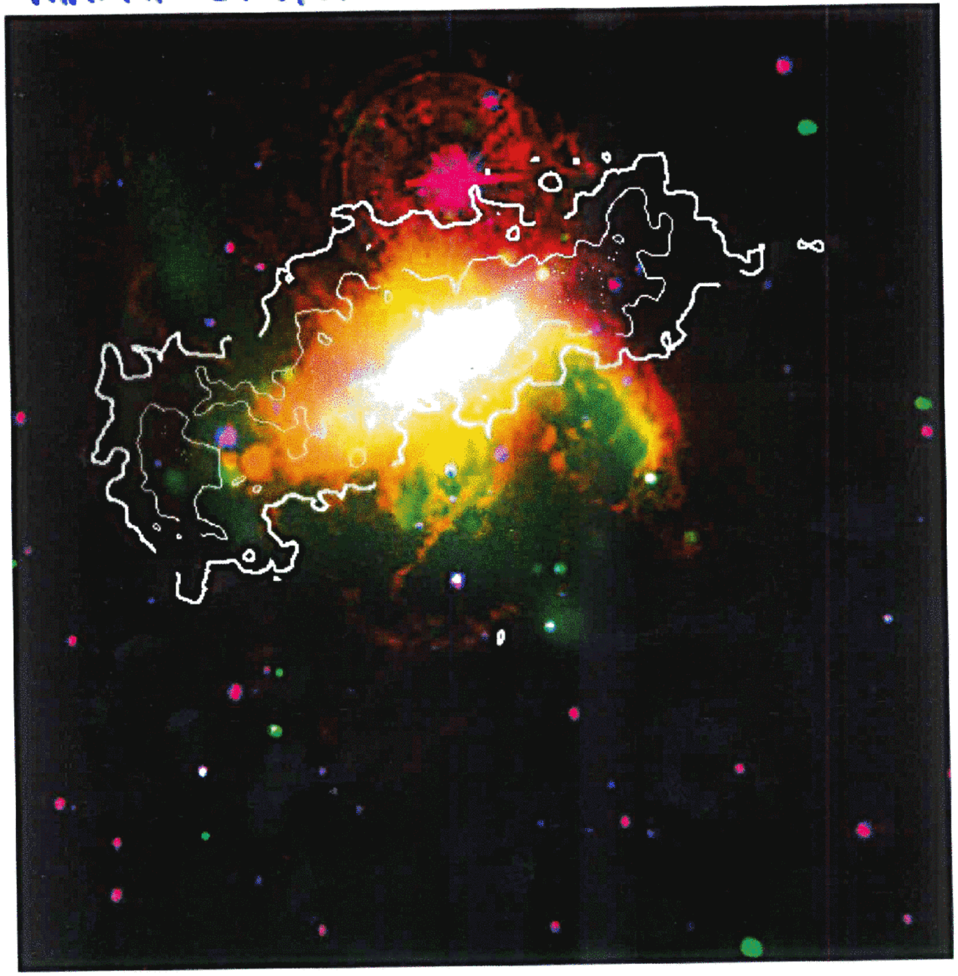

Thermal X−ray Luminosity vs Gas Temperature
Temperature (keV)
0.2
0.4
0.6
0.8
L_thermal 0.3−2.0 (10^39 ergs/s)
0.1
1
10
100
1000

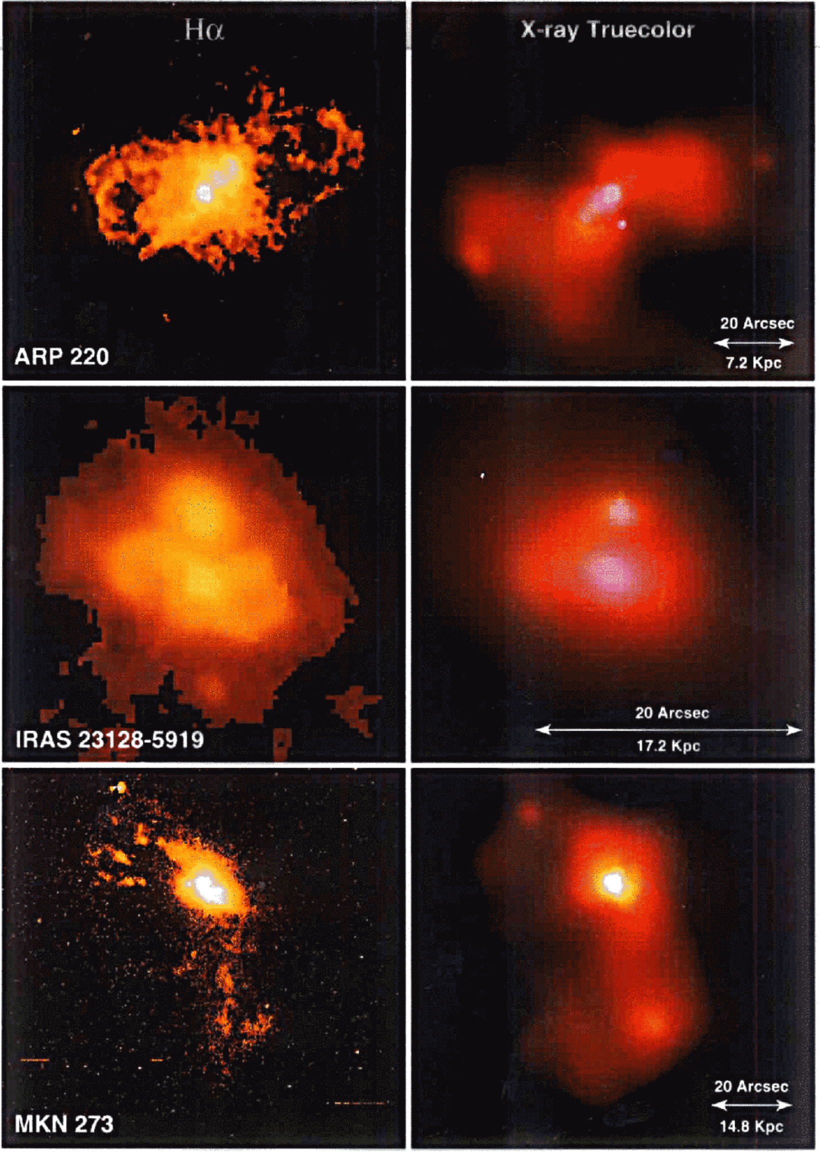

90% Flux Enclosed Surface Brightness vs FIR Luminosity
Surface Brightness at 90% Flux Enclosed
10^{-6}
10^{-7}
10^{-8}
10^{-9}
L_{FIR} $(10^{10}\ L_\odot)$
0.1
1
10
100


Ratio of Thermal X-ray to FIR Luminosity vs FIR Luminosity
$L_{Total\ Mekal\ 0.3-2.0\ keV}/L_{FIR}$
10^{-3}
10^{-4}
L_{FIR} $(10^{10}\ L_\odot)$
0.1
1
10
100

NGC1569 Chandra + Hα + HI

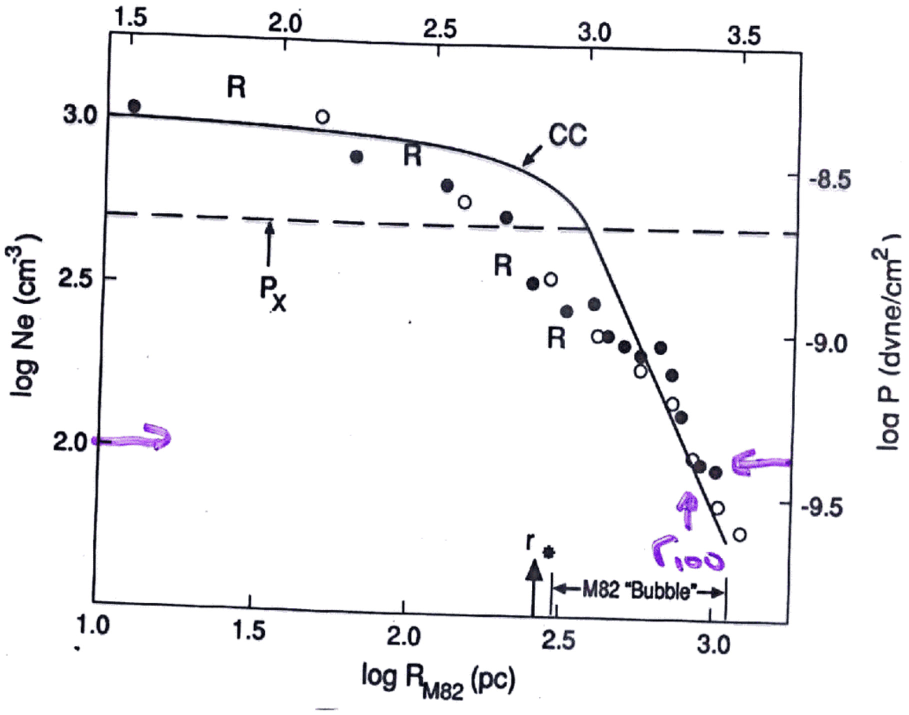
MARTIN ET AL.





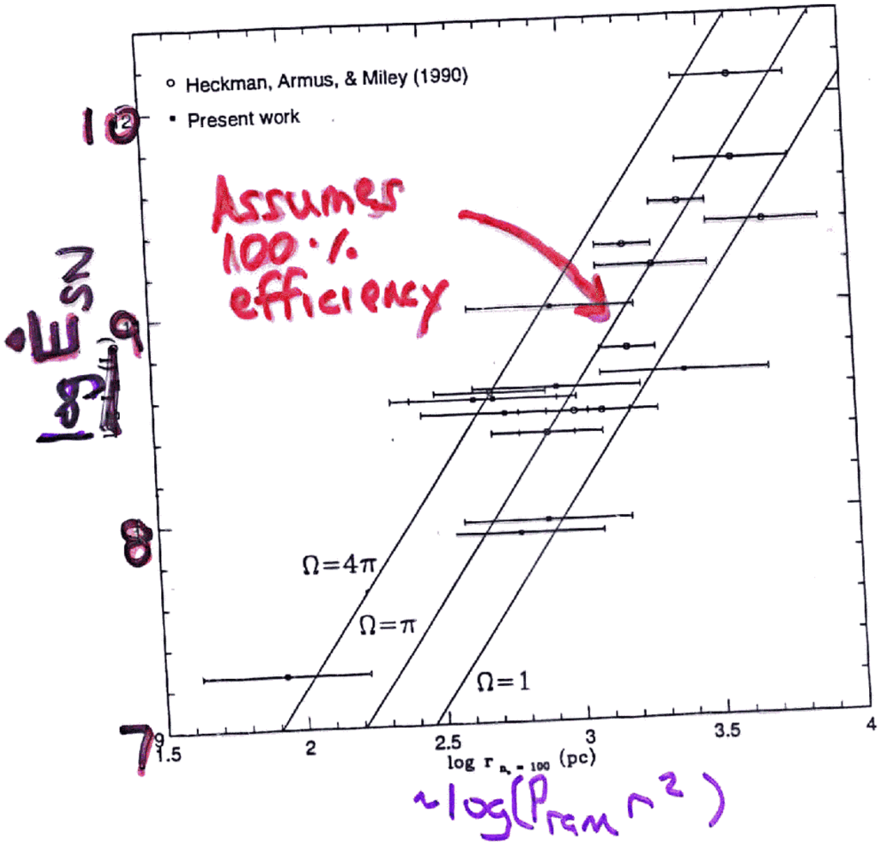
Heckman, Armus, & Miley

STARBURST-DRIVEN GALACTIC SUPERWINDS

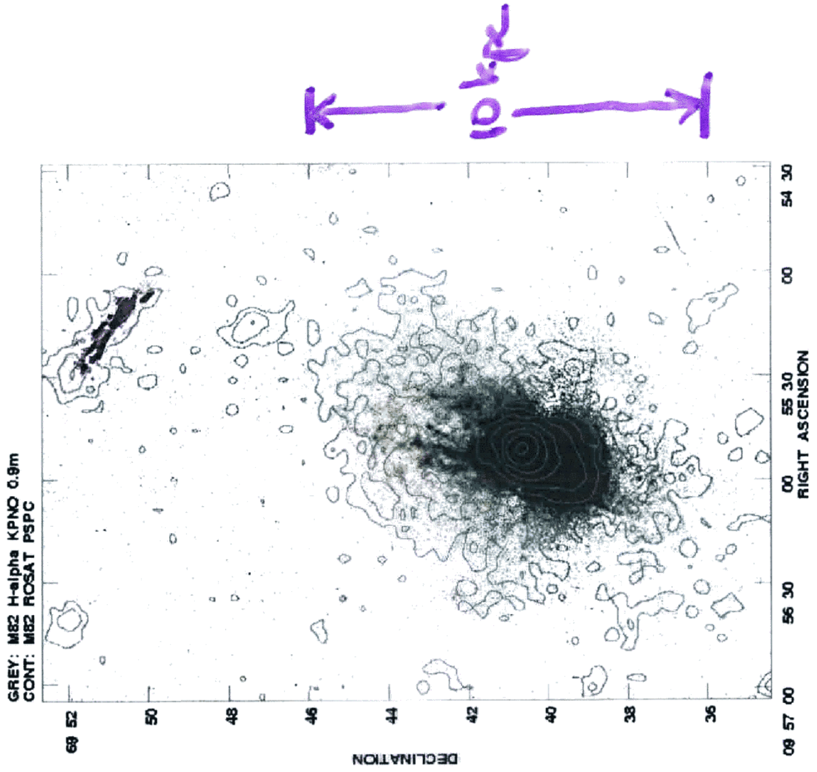


Isobaric radius vs. L_{BOL}

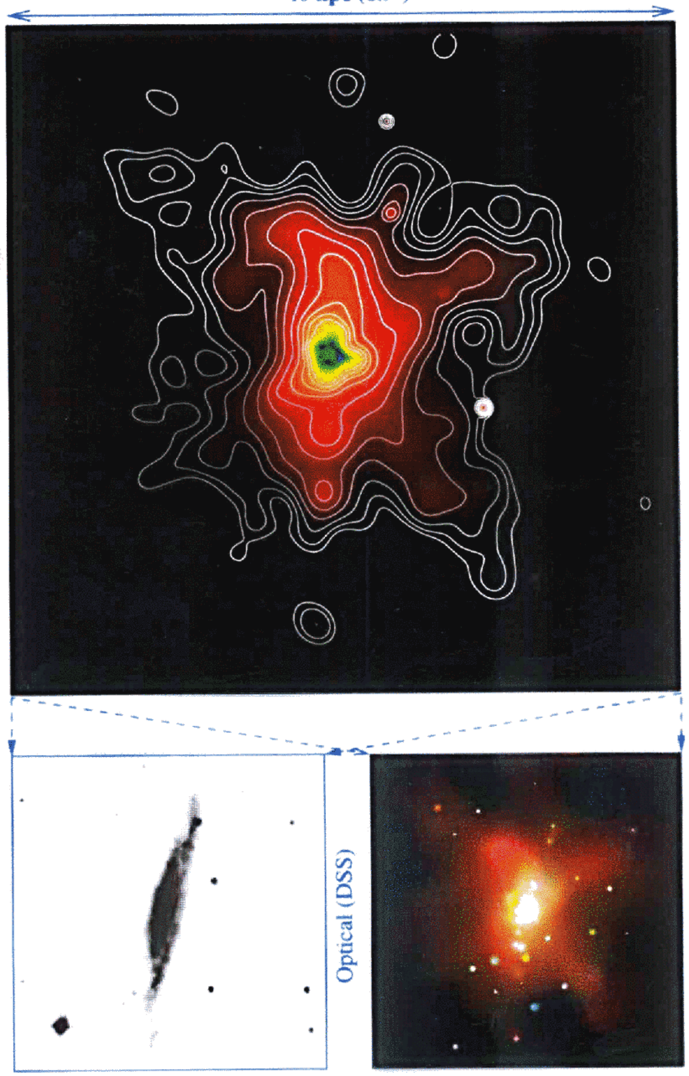
Lehnert & Heckman



Lehnert, Heckman, + Weaver

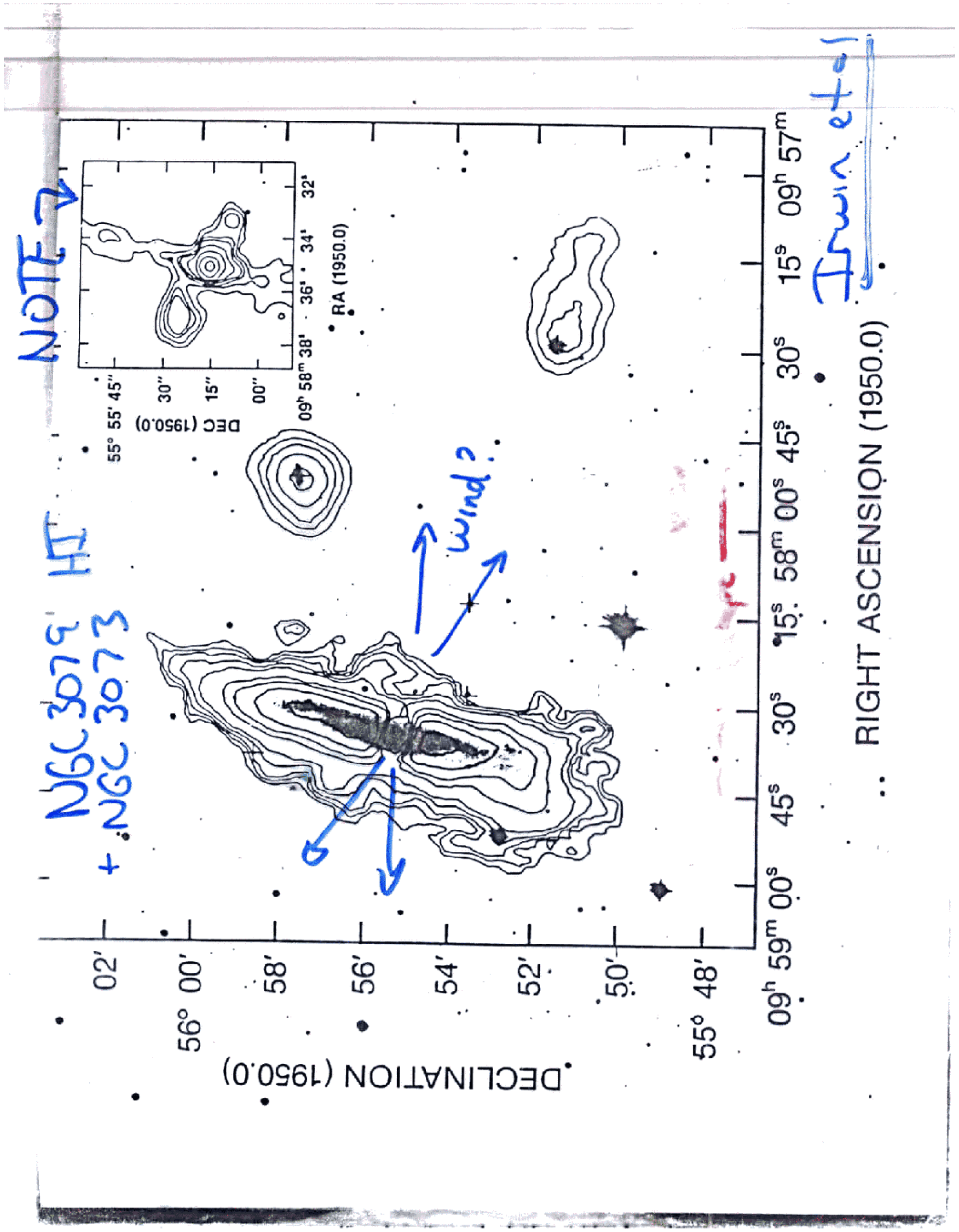


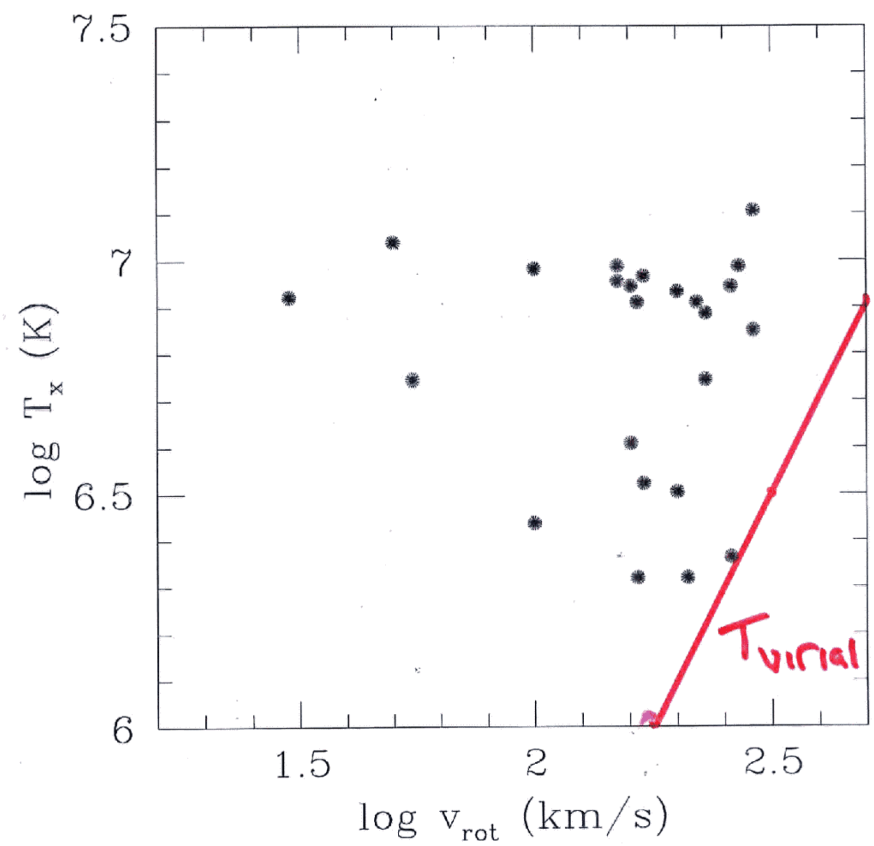
NGC 3079



Chandra ACIS-S3 (0.3–2.0 keV). Point source-subtracted.
Square root intensity scale (1e-6 to 1e-2 cts/s/arcsec^-2)
Contours begin at 5e-7 cts/s/arcsec^-2 and increase by factprs of $2^{1/2}$

Energy coded X-ray
0.3–1.0 keV 1–2 keV
2–8 keV


NOTE ↓
NGC 3079 HI
+ NGC 3073
wind?
Irwin et al
RIGHT ASCENSION (1950.0)
DECLINATION (1950.0)
09h 57m
15s
30s
45s
58m 00s
15s
30s
45s
09h 59m 00s
02'
56° 00'
58'
56'
54'
52'
50'
55° 48'
RA (1950.0)
32s
34s
36s
38s
09h 58m
DEC (1950.0)
55° 55' 45"
30"
15"
00"


log T_x (K)
log v_{rot} (km/s)
7.5
7
6.5
6
1.5
2
2.5
T_{virial}

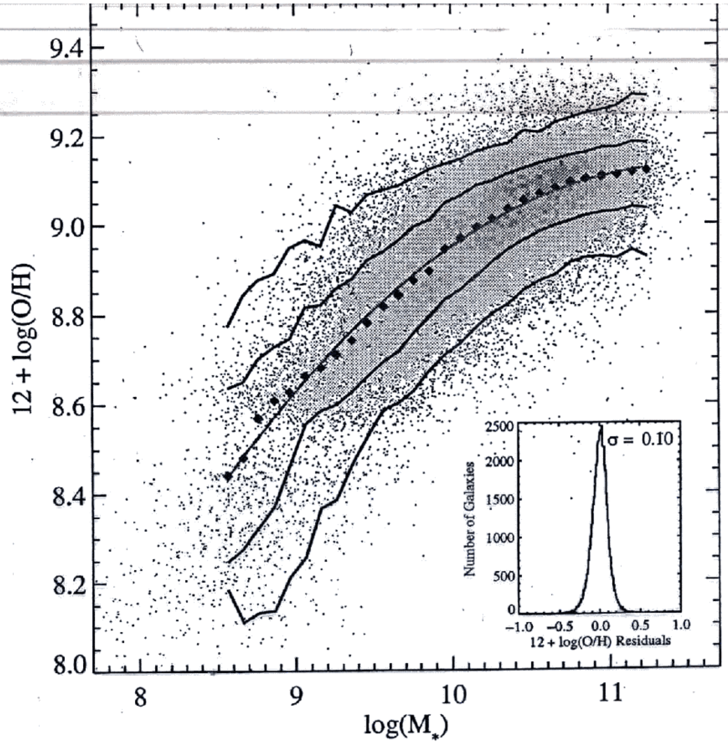


FIG. 6.— The relation between stellar mass, in units of solar masses, and gas-phase oxygen abundance for ~53,400 star-forming galaxies in the SDSS. The large black points represent the median in bins of 0.1 dex in mass which include at least 100 data points. The solid lines are the contours which enclose 68% and 95% of the data. The red line shows a polynomial fit to the data. The inset plot shows the residuals of the fit. Data for the contours are given in Table 3.

Tremonti et al.