H II Nuclei in Nearby Galaxies

Wendy Hawley
Journal Club 2/23/07

“Properties of H II Regions in the Centers of Nearby Galaxies” (Ho, L.C., Filippenko, A.V., & Sargent, W.L.W. 1997, ApJ 487, 579)

"Dynamical Evidence a for Massive, Young Globular Cluster in NGC 1569" (Ho, L.C. & Filippenko, A.V. 1996, ApJ 466, L83)

Outline

- H II Regions in Nearby Galaxies
  - Motivation
  - The New Survey
  - Basic Properties of Nuclear H II Regions
  - Discussion
  - Summary
- Evidence for a massive, young GC in NGC 1569

Motivation

- Understanding H II regions can lead to an understanding of other problems in astrophysics
- H II nuclei serve as probes of massive star formation
- More feeble in output than starburst nuclei, but there are a large # of nearby H II nuclei
- Comparison with disk H II regions gives insight
- This paper uses a new survey to study H II nuclei

The New Survey

- optical spectroscopic survey of bright nearby galactic nuclei (Ho, Filippenko & Sargent 1995)
- used Hale 5m at Palomar to obtain high S/N, moderate-resolution (100-200 km/s) spectra
- galaxies sample: all galaxies in the Revised Shapley-Ames Catalog of Bright Galaxies with $\delta > 0$ degrees and $B_T \leq 12.5$ mag
- nearly statistically complete and contains 486 galaxies over a range of all morphological types
- because of the size of sample and selection criteria, the sample is a fair representation of local ($z \sim 0$) high surface brightness galaxies

H II nuclei detected

- dominant ionization mechanism for each nucleus determined by looking at intensity ratios for prominent optical emission lines
- H II nuclei, like disk H II regions, are defined by photoionization by UV radiation from young, massive stars as primary source of ionization
- from 4200-6900 Å, strongest emission lines from hydrogen recombination and [O III] λλ4959, 5007
- strength of [O III] lines relative to hydrogen depends on excitation
- H II nuclei distinguished from AGNs by comparitively weak low-ionization transitions of [N II] λλ6548, 6583, [S II] λλ 6716, 6731, and [O I] λλ6300, 6363
- 206 total H II nuclei detected, ~80% observed under photometric conditions

Uncertainties

- data contains limited spatial information
- Pogge (1989) found that H II nuclei line emission patterns are complicated and extended
- spectra extracted from a fixed aperture, therefore physical size varies depending on distance
- uncertainty for extended line-emitting material: flux will be underestimated
- uncertainty for compact emission: flux may be overestimated due to integration over several discrete and possibly overlapping regions
- sample is large, so the individual fluctuations should average out

Comparison Data

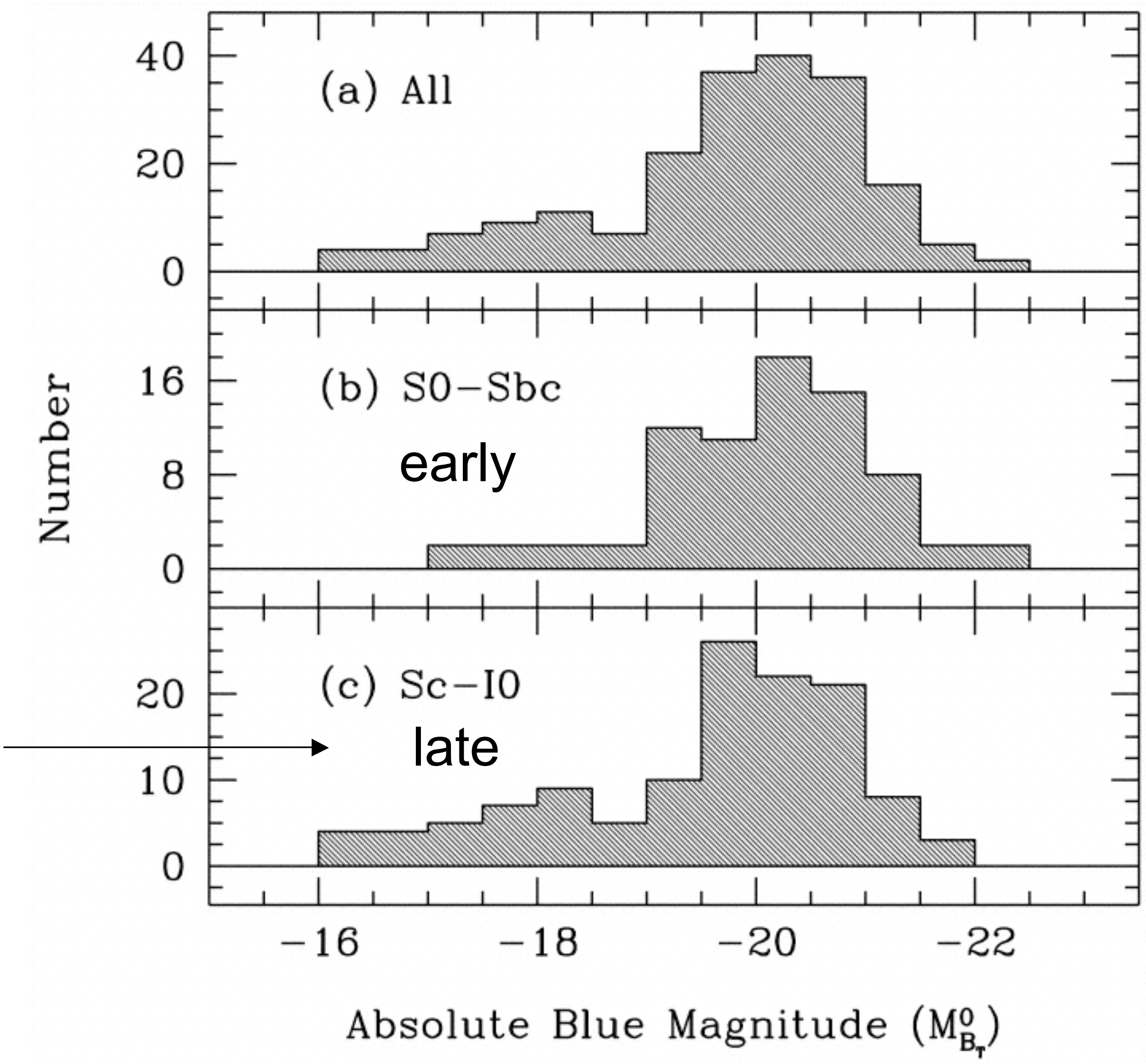
- comparison to starburst nuclei:
  - 62 objects in French (1980), Balzano (1983), and Veilleux & Osterbrock (1987) for forbidden-line intensities and 98 objects in Balzano (1983) for Hα luminosities
- comparison to disk H II regions:
  - line-intensity ratios for ~200 regions in disks from McCall et al. (1985), Ryder (1995). line measurements for dwarf irregulars from French (1980) and Dinerstein & Shields (1986). Hα luminosities for 95 disk H II regions from Kennicutt (1988)

Basic Properties of H II Nuclei

- H II nuclei 42% of all galaxies with $B_T<12.5$ mag
- Late-types contain H II nuclei more frequently than early-types (Sc-Im: up to 80%, Sb: 51%, Sa: 22%, S0: 8%, none in ellipticals)
- galaxies with H II nuclei are less luminous than those with AGN
- early refers to S0-Sbc, late refers to Sc-I0, and six peculiar galaxies omitted

FIG 1

Luminosity Distribution



early

late

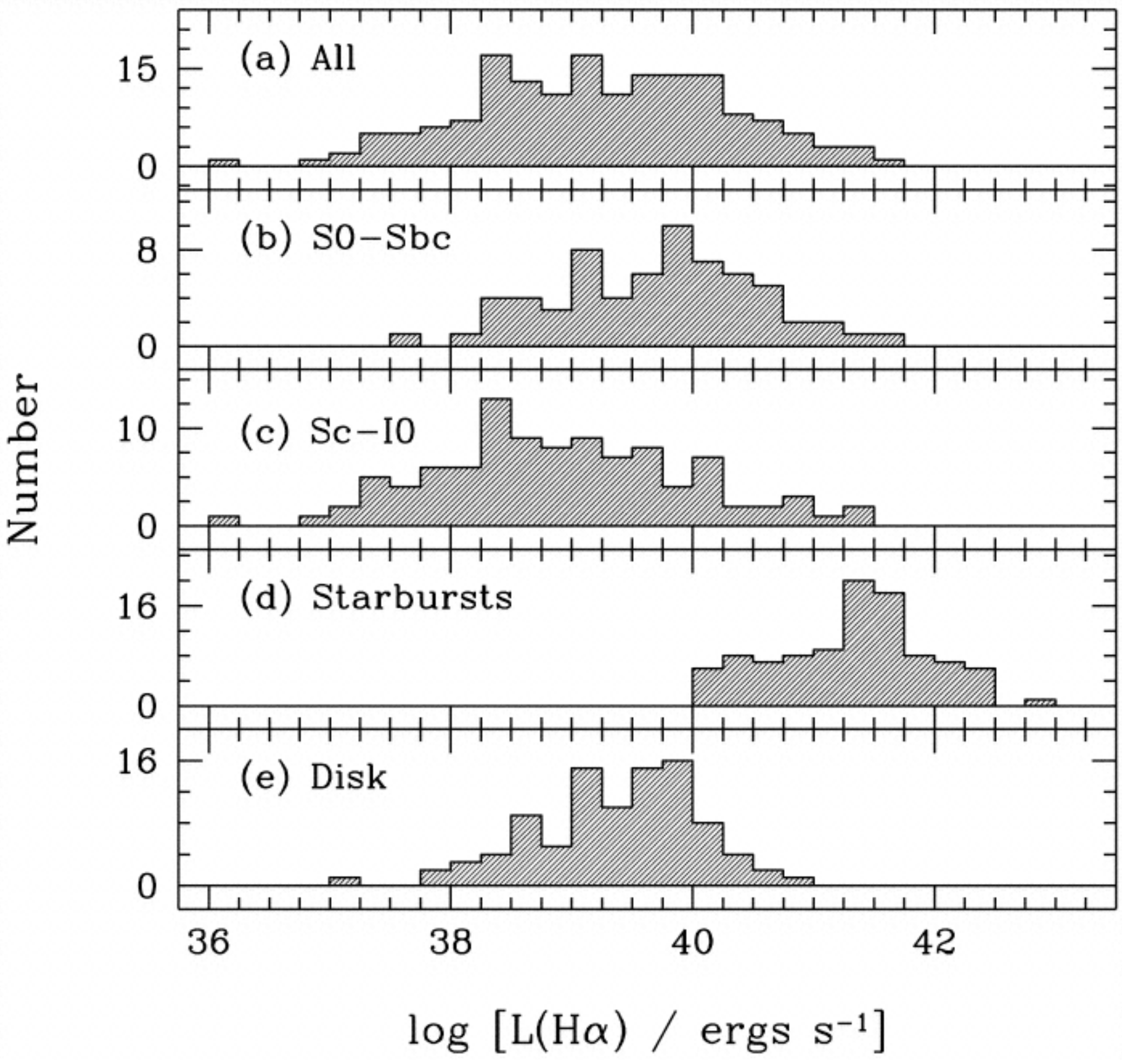
Less luminous, but overlapping with early

Barred Statistics

- 50-60% of disk galaxies in survey are barred (about the same as general galaxy population)
- barred systems should have enhanced star formation at centers
- evidence found for increased star formation rate in barred sample
- bars exert greatest impact on star formation in early-type nuclei and minor effects in late-types

FIG 2

Hα luminosity Distribution



Early- and Late-type difference

- from Kolmogorov-Smirnov (K-S) test, the probability the early and late types are drawn from the same population is only $P_{KS}=1.9 \times 10^{-5}$
- The difference in luminosities cannot be due only to the difference in median distance (21.5 Mpc for early and 16.9 for late)
- If surface brightness of Hα emission constant in central regions of both groups, it would only account for a 70% difference
- the real reason: enhancement of central star formation from bar-driven gas inflow, which affects only resulting early-type systems

FIG 3

Balmer Equiv. Widths

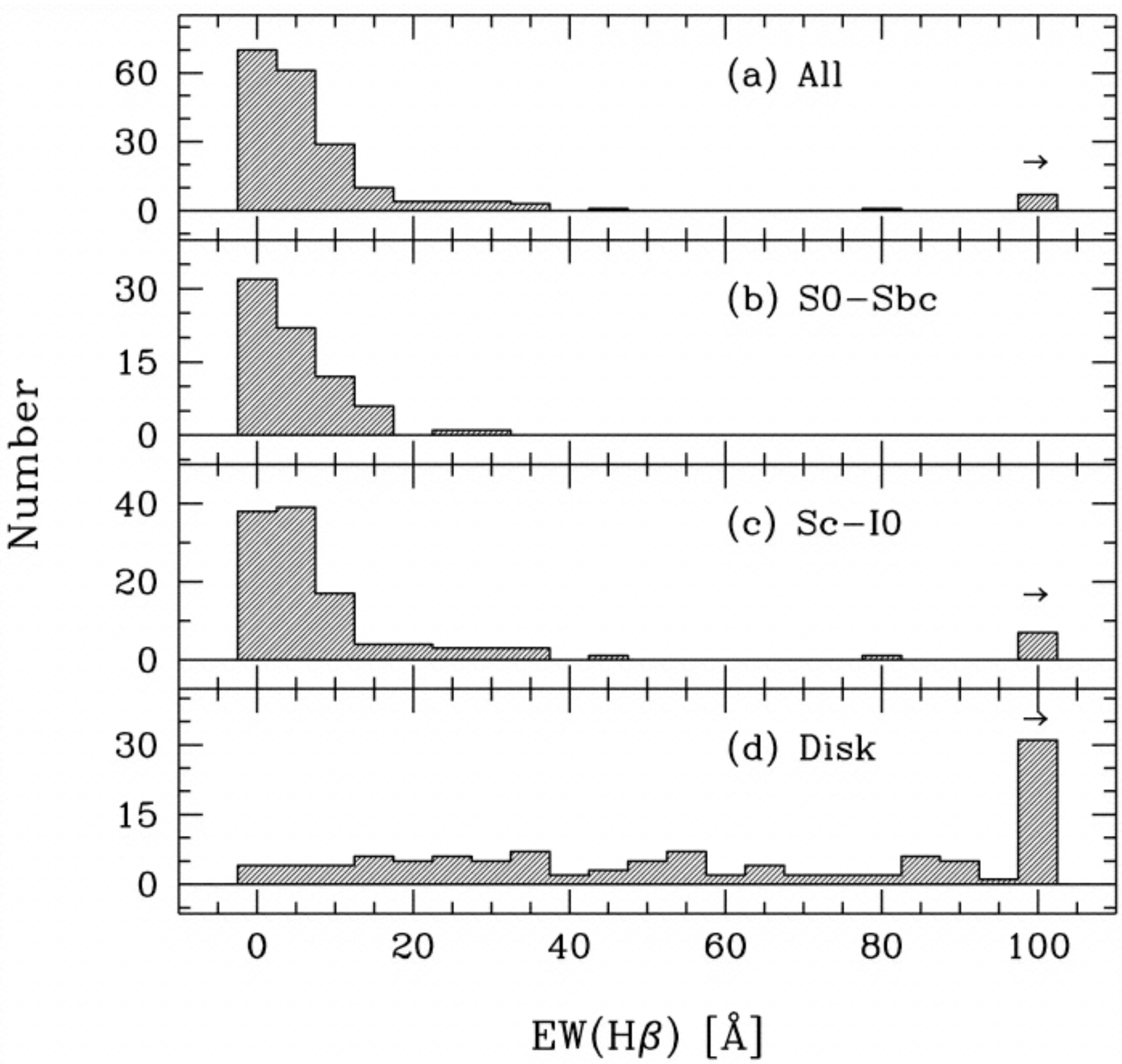
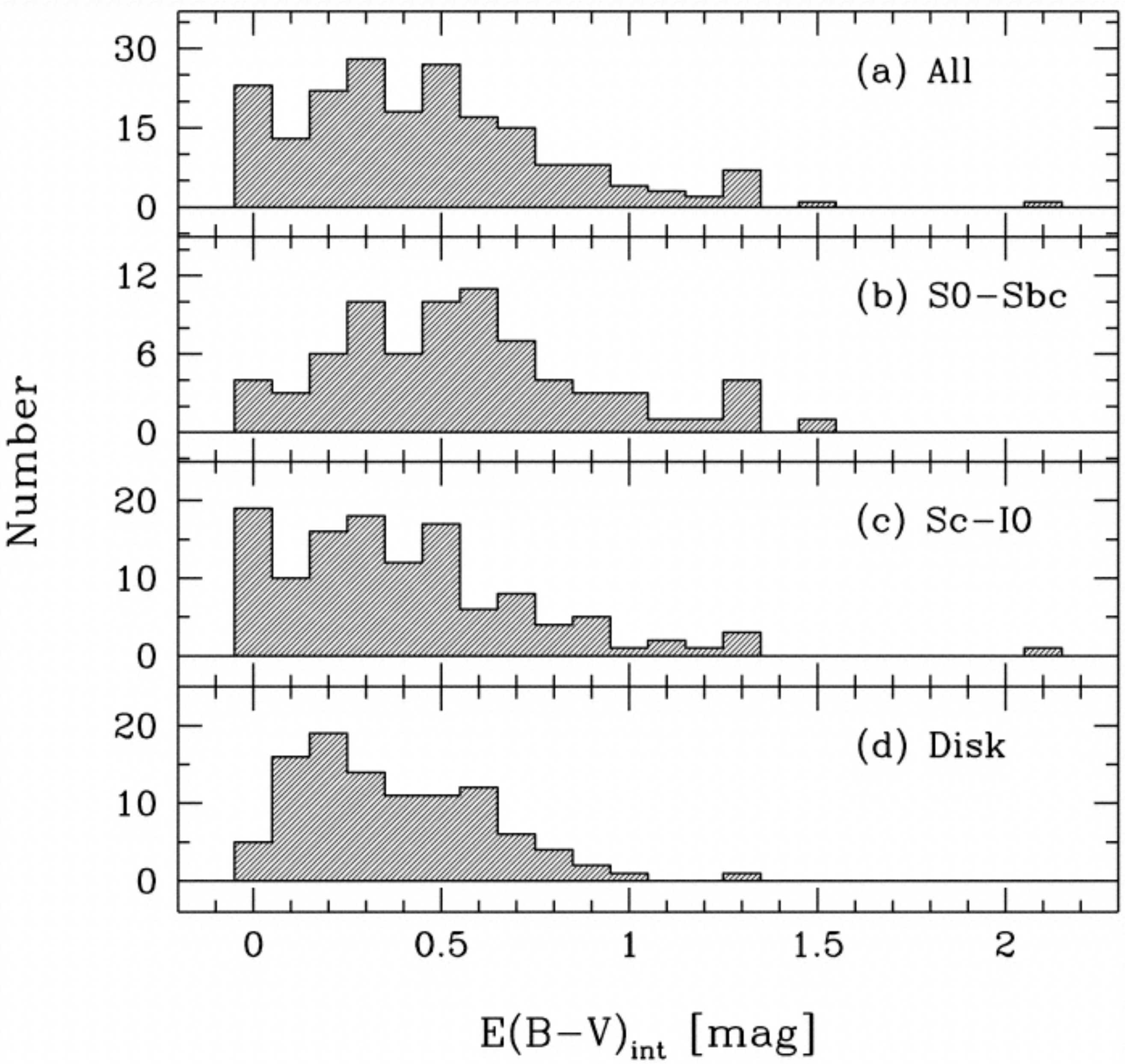


FIG 4

Reddening



Reddening Uncertainty

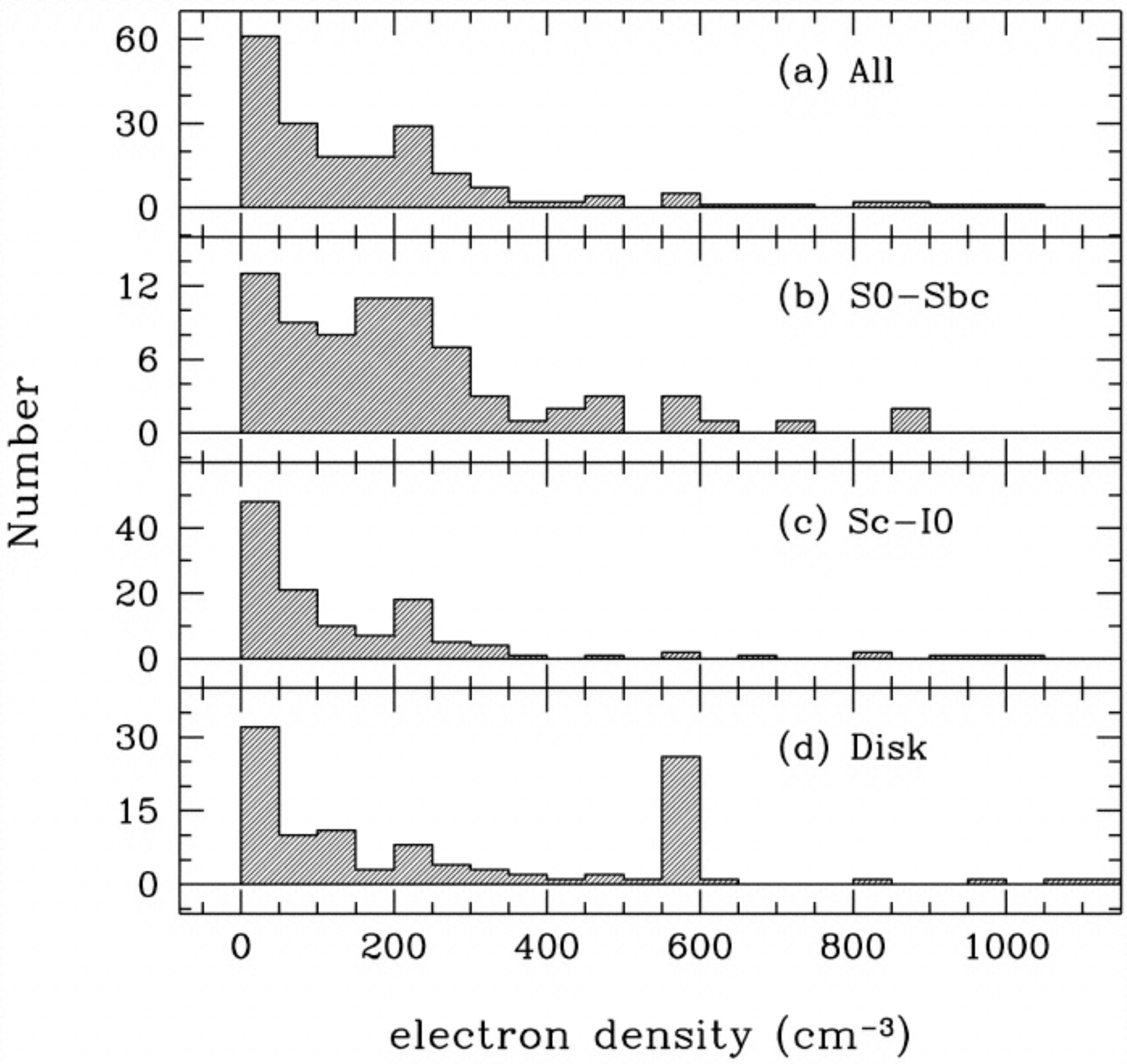
- K-S test shows difference is significant between disk and early-type ($P_{KS}=0.0022$), but insignificant between disk and late-type ($P_{KS}=0.29$)
- uncertainty: unknown source of systematic error may cause higher value of reddening for early-type galaxies
- although this affects quantitative results, the conclusions should be the same
- potentially worse uncertainty is the lack of knowledge about total extinction in galactic nuclei
- method: using Balmer decrement to estimate extinction assumes uniform foreground dust screen, which is especially an oversimplification in nuclear regions
- measure free-free continuum in radio wavelengths would be better, but hasn't been applied to nuclei

Electron Density Determination

- n_e found by using the density-sensitive [S II] λλ 6716, 6731 doublet, which fall on an uncomplicated part of the stellar continuum
- deblending is made easier by moderately high resolution of red spectra
- [S II] λλ6716, 6731 calculated assuming electron temp of 10^4 K and latest atomic parameters for S^+
- also re-derived disk n_e values

FIG 5

Electron Densities



Electron Density Difference

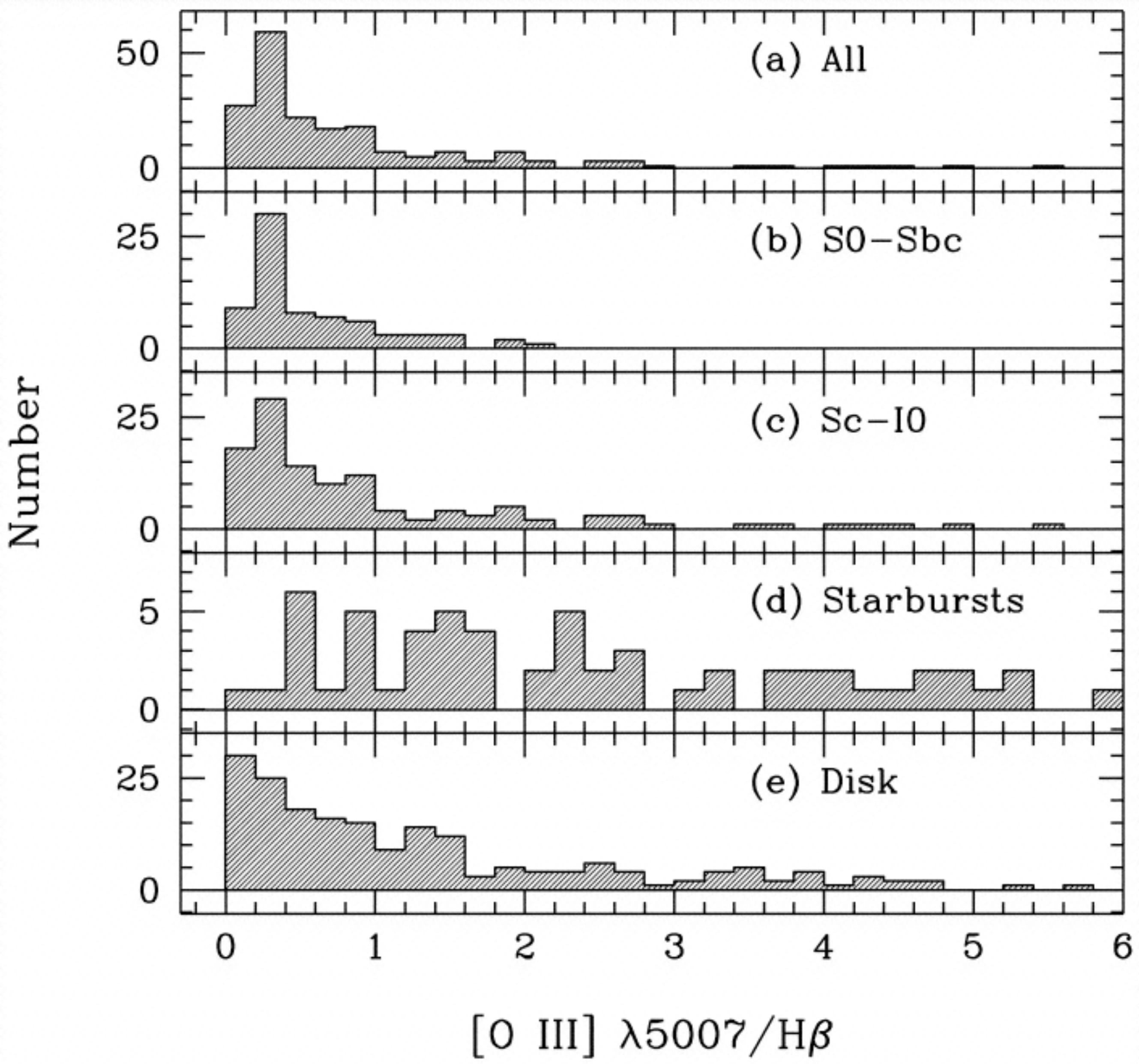
- P_{KS}=0.0016: unlikely difference is influenced by systematic errors, region used is uncomplicated
- using a value of temp of 5×10^3 K for instance only decreases early-type median density by 25% with P_{KS}=0.0079)
- Could be due to bulge dominance – bigger bulge, larger pressure, higher density
- But then why isn’t nuclear region more dense than disk region?

H II Mass and Filling Factors

- Estimated ionized hydrogen mass by combining extinction corrected Hα luminosities with electron densities
- For H II nuclei: 10^2-10^6 $M_\odot$ with median 10^5 (disk regions similar)
- H II mass of early type about 2-3 times larger than late type
- volume filling factors found by assuming line-emitting material has dimensions about the size of aperture
- filling factors 10^{-6}-10^{-1}, most around 10^{-5} with no large variation in Hubble type
- In agreement with Kennicutt, Keel & Blaha (1989, hereafter KKB), ionized gas in nuclear regions clumpier than in disk regions

FIG 6

Exciting! Excitations



Oxygen Abundances

- oxygen abundance found usually by using R_{23}
- early-type: range ~0.1-2.0, median 0.4
  - 12+log(O/H): range 8.88-9.36, median 9.16
  - solar abundance 8.84, so these values have range 1.1-3.3 times solar and median 2.1 times solar
- late-types range ~0.06-5.5, median 0.6 (1.9 times solar)
  - lower bound uncertain because O/H calibration double valued at low O/H values
- starbursts: excitation is higher than nuclei, (contrary to Balzano's findings)
- Are starbursts predecessors of H II nuclei?
- Fits with high luminosity and lower metal abundance (median ~ solar)

FIG 7

From Veilleux & Osterbrock (1987)

- disk H II regions
- ○ H II nuclei
- * starburst nuclei

Dashed curve: McCall et al. (1985) model disk regions

Dotted curves: Shields & Kennicutt (1995) photoionization model with dust effects

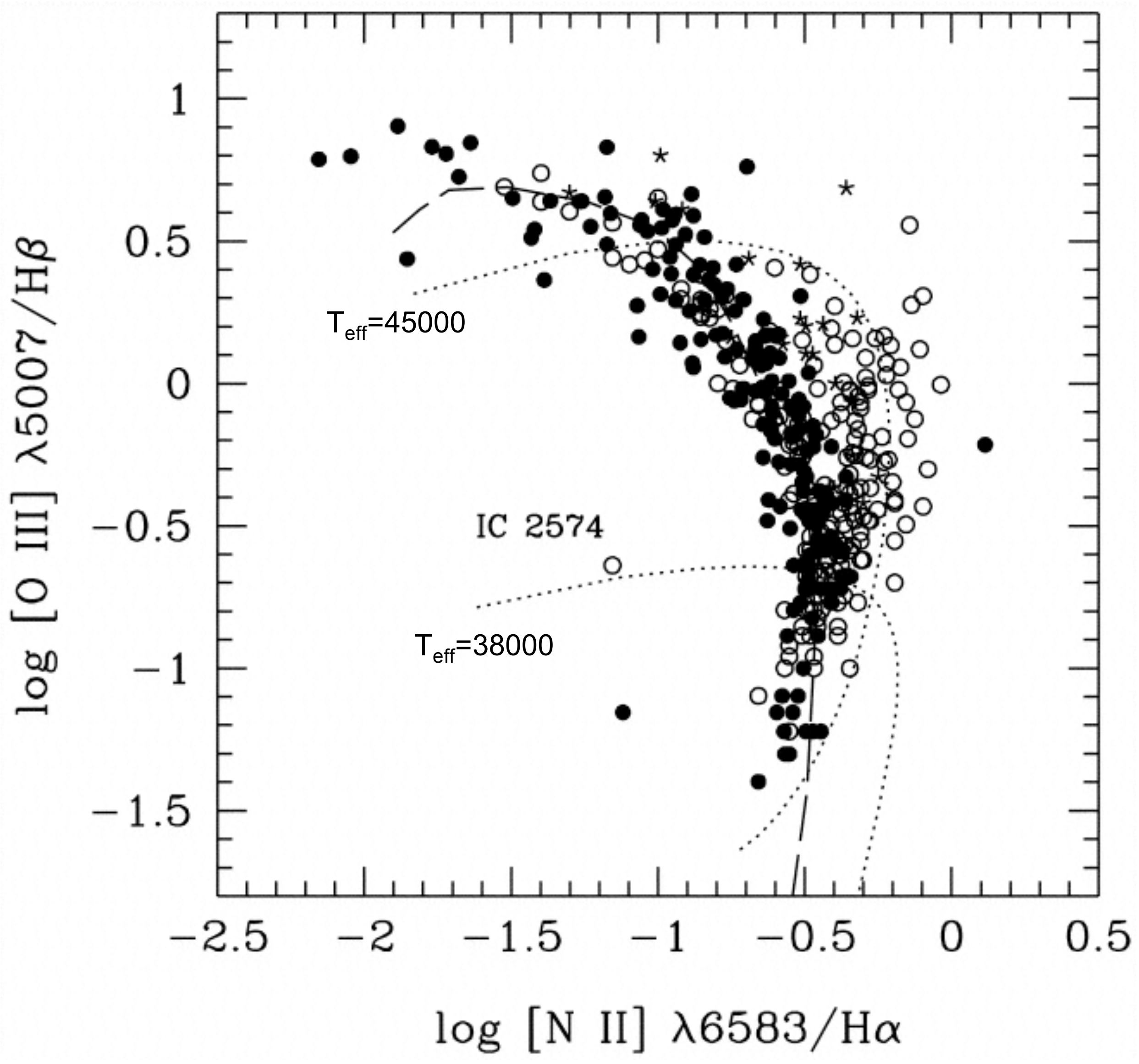


FIG 8

More line ratios

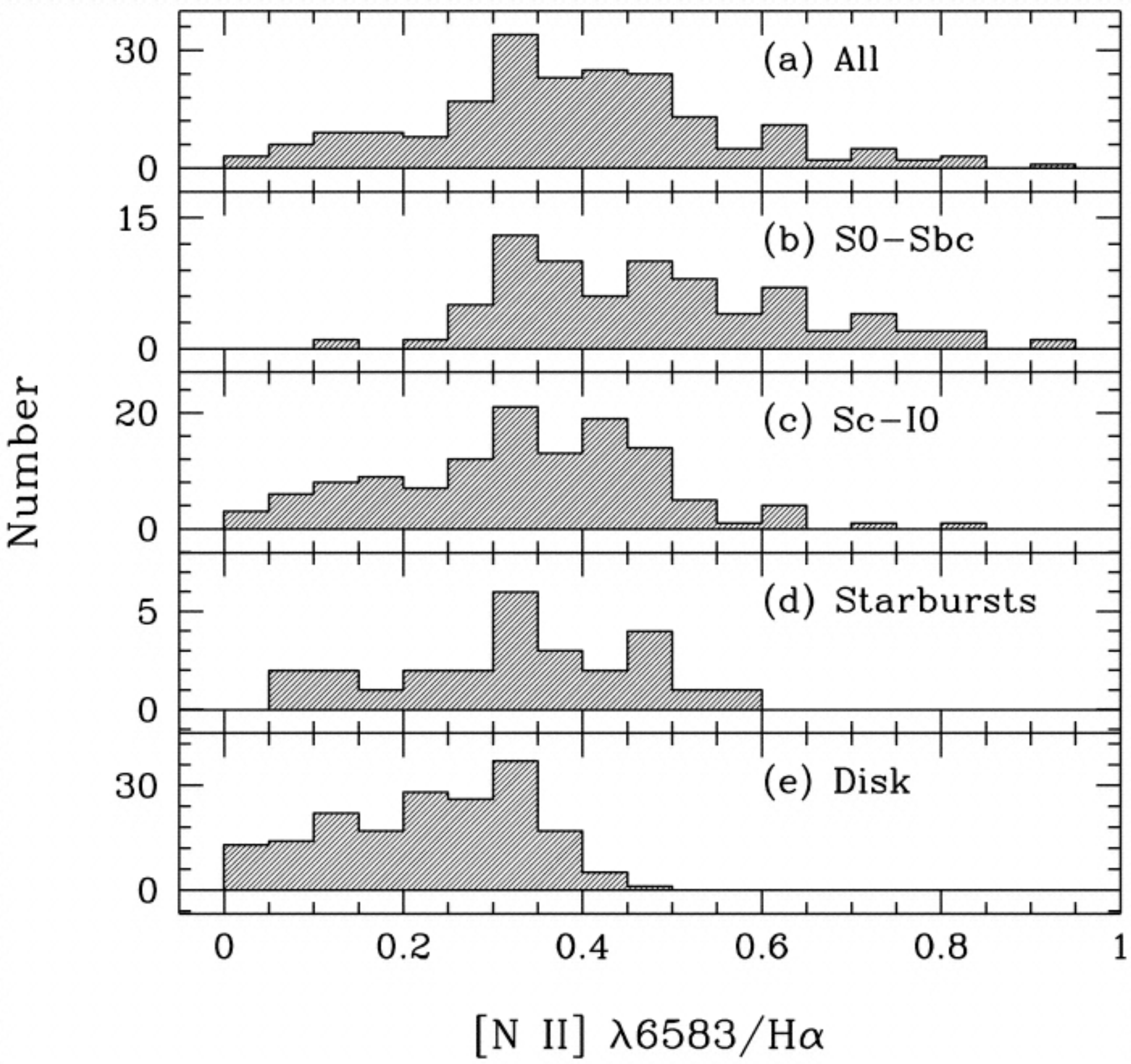


FIG 9

- ● early-type nuclei
- ○ late-type nuclei

Dashed curve: McCall et al. (1985) model disk regions

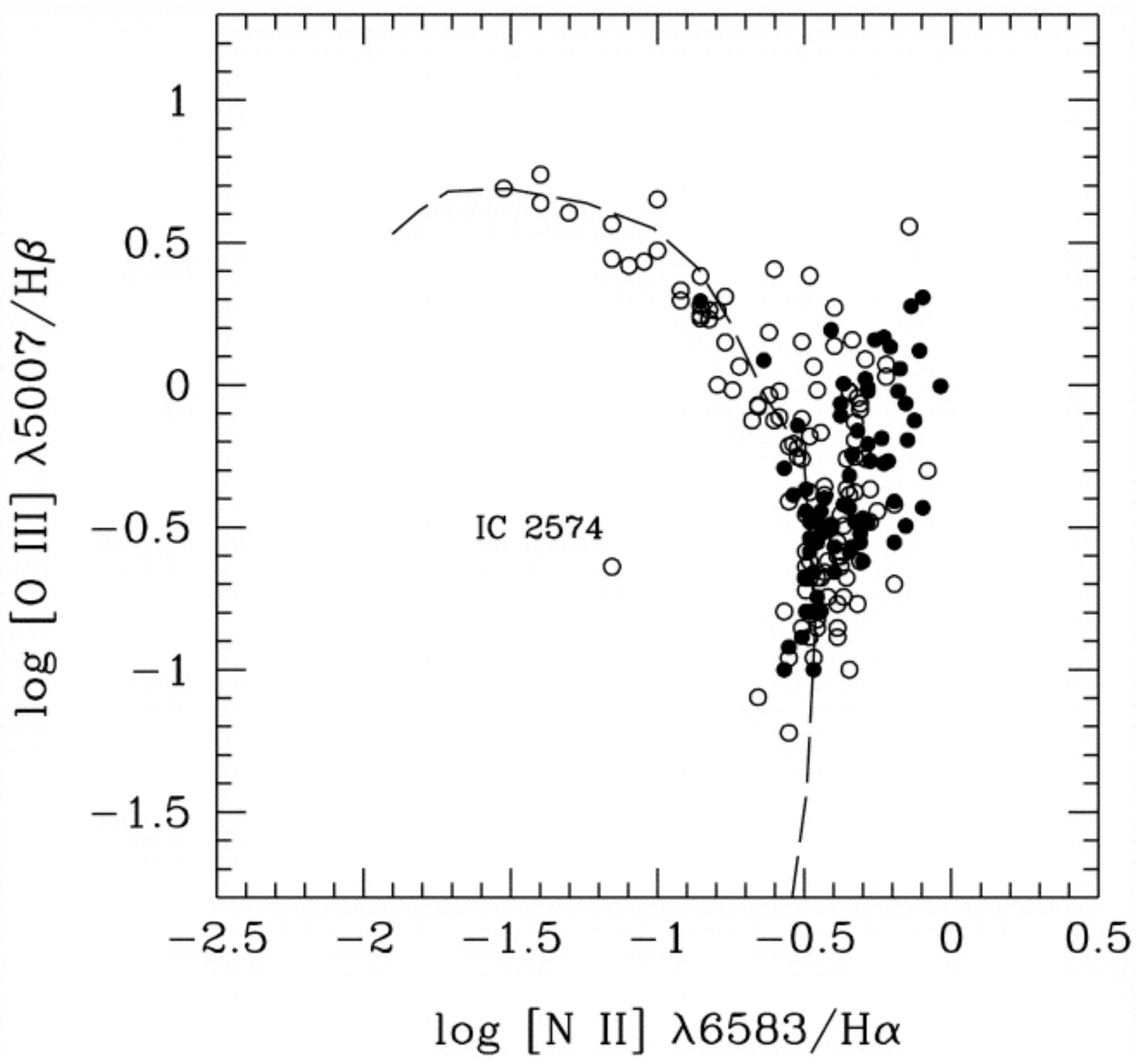
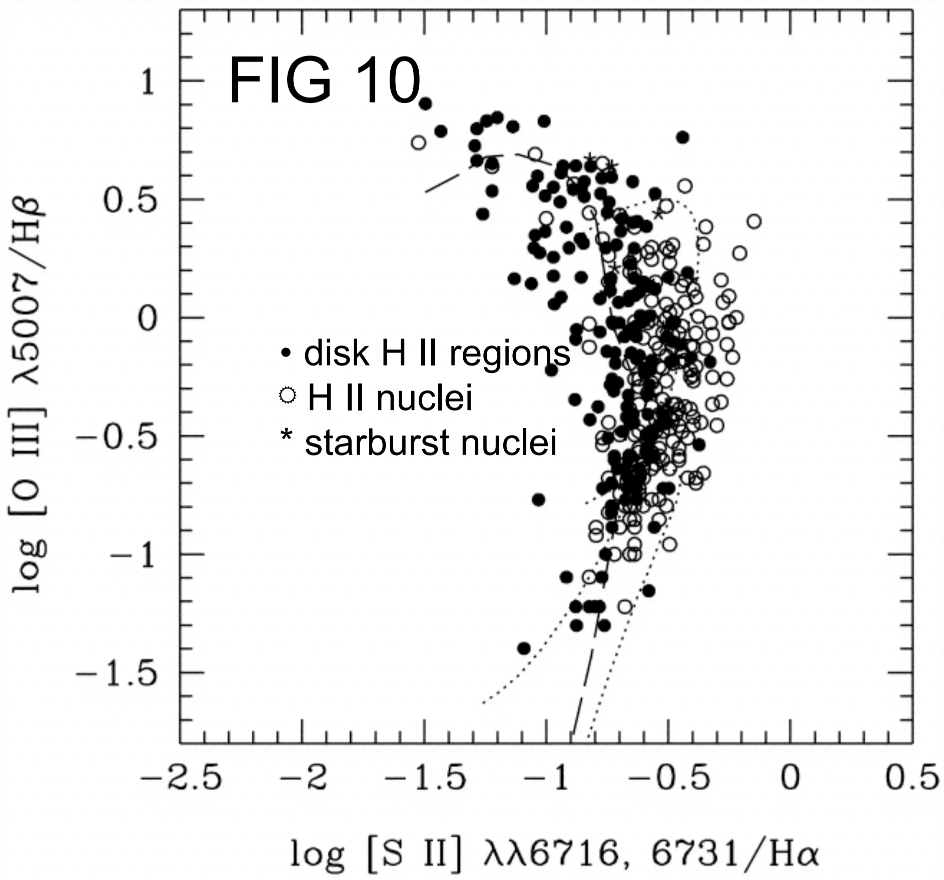


FIG 10



Dashed curve: McCall et al. (1985) model disk regions

Dotted curves: Shields & Kennicutt (1995) Photoionization model with dust effects

FIG 11

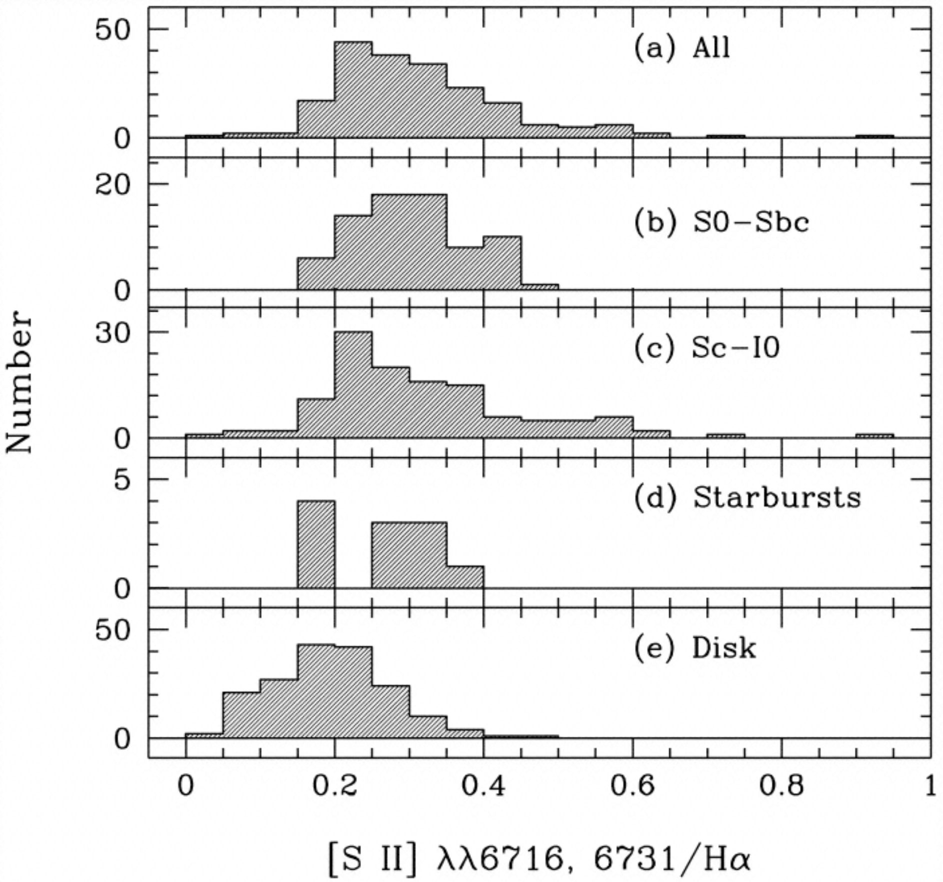
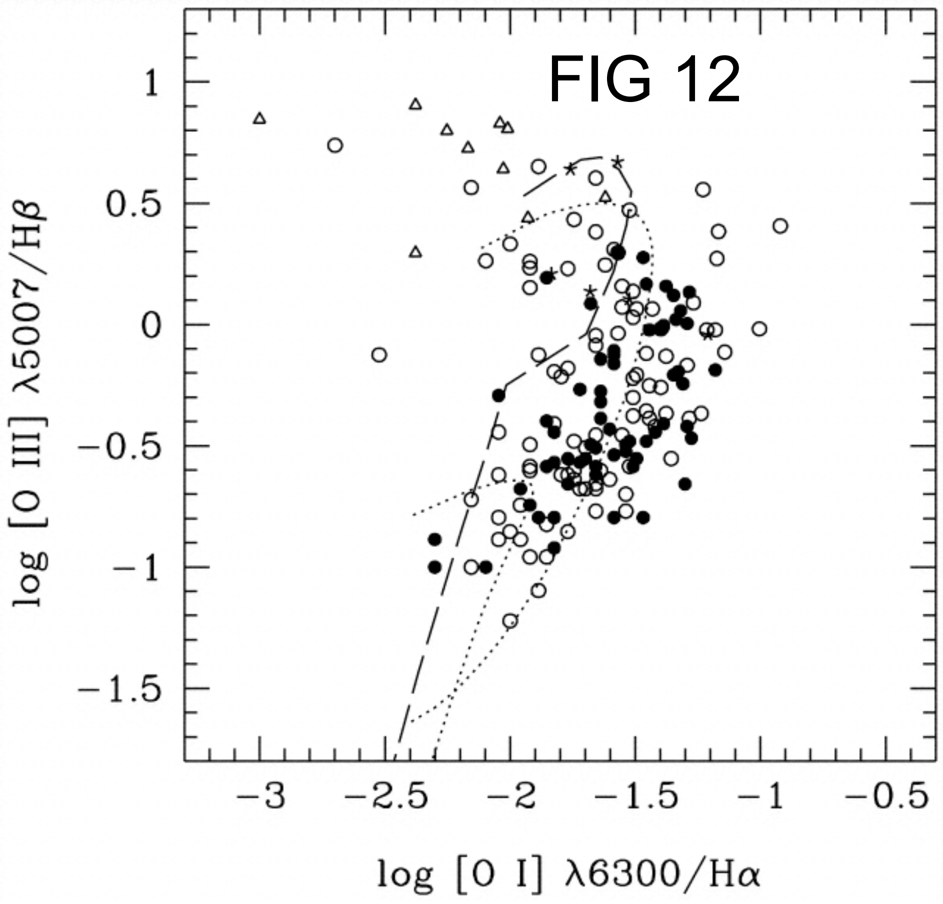


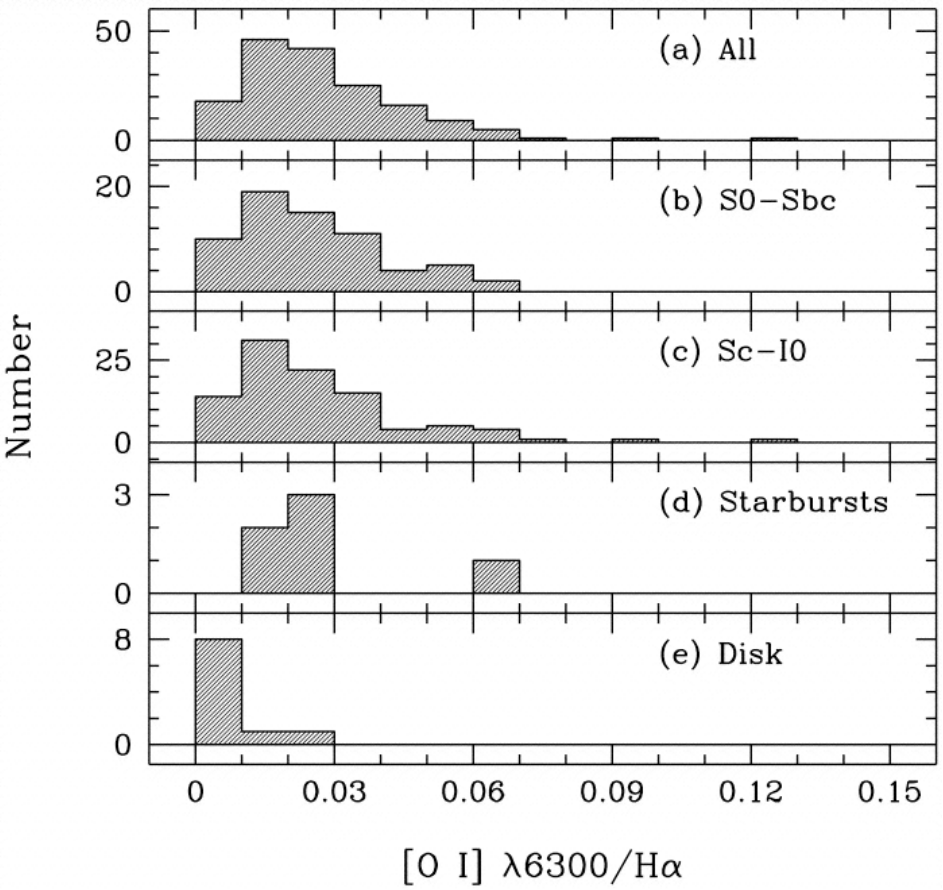
FIG 12



Dashed curve: McCall et al. (1985) model disk regions

Dotted curves: Shields & Kennicutt (1995) Photoionization model with dust effects

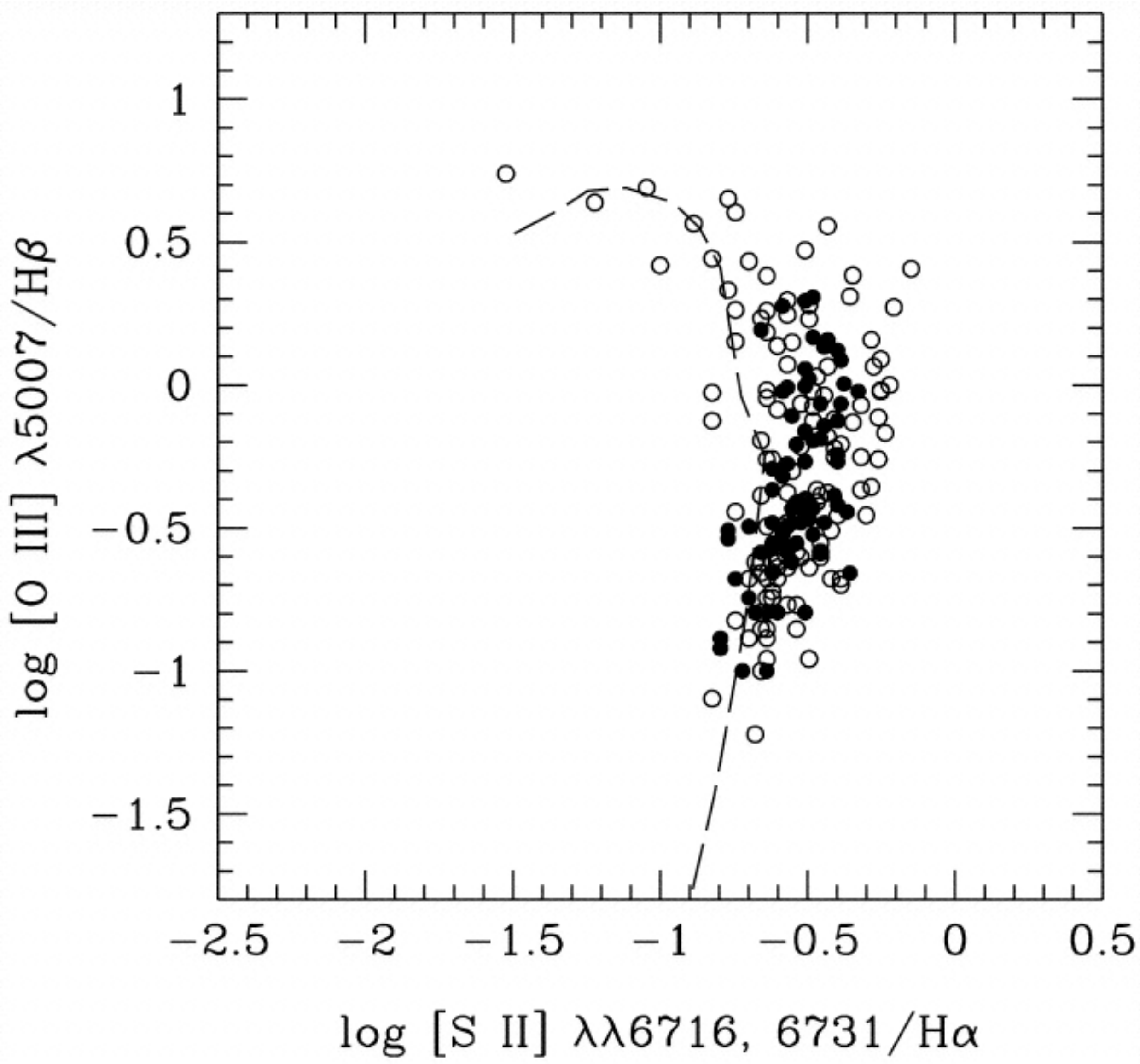
FIG 13



Caution about [O I]

- Models are observationally unverified
- [O I] line emits from a region that is very thin and has a high dependence on structure of nebula
- Campbell (1988): theoretical models of high-excitation H II regions “underpredict” [O I] strengths by large factors
- [O I]/Hα also has larger scatter than other two

FIG 14



- ● early-type nuclei
- ○ late-type nuclei

Dashed curve:
McCall et al. (1985)
model disk regions

Enhancement of Low-Ionization Lines

- Verify KKB’s finding that H II nuclei emit stronger low-ionization forbidden lines than disk regions
- Stauffer (1981): noticed effect in [N II]/Hβ ratio, suggested shock-wave heating
- Veilleux & Osterbrock (1987): no obvious difference - small sample?

Explanation #1: AGN

- KKB: low-ionization enhancement due to weak AGN
- AGN have harder ionizing spectra than O and B stars
- Genuine composite nuclei are known, and there are some optical spectra between H II nuclei and AGNs
- Weak active nuclei could be revealed in radio, UV or x-ray

Explanation #2: Shocks

- Collisional excitation by shocks from supernova remnants (SNRs)
  - Improbable because the # of SNRs required is excessive
- Shocks from bulk or turbulent motions of gas probable
  - High velocities (compared to disk regions) and non-circular motions in nuclear regions
  - The observed "excess" could be explained this way

Explanation #3: Photoionization

- Filippenko & Terlevich (1992) and Shields (1992): O stars with high T_{eff} (45000-50000 K) combined with low ionization parameters
  - Low-Ionization Nuclear Emission-line Regions (LINERs)
  - Depart from inverse correlation between T_{eff} and metallicity seen in disks
  - Lower ionization parameters could tie in with lower volume filling factors

Explanation #4: Dust

- Mathis (1986): Dust effects minimal
- Shields & Kennicutt (1995): in higher than solar metallicity regions, dust enhances forbidden emission (increases T_e through depletion of coolants)
  - Could explain effect if higher metallicity is accompanied by higher dust content
  - In previous figures, dust model was an okay fit to data

Explanation #5: “diffuse ionized gas”

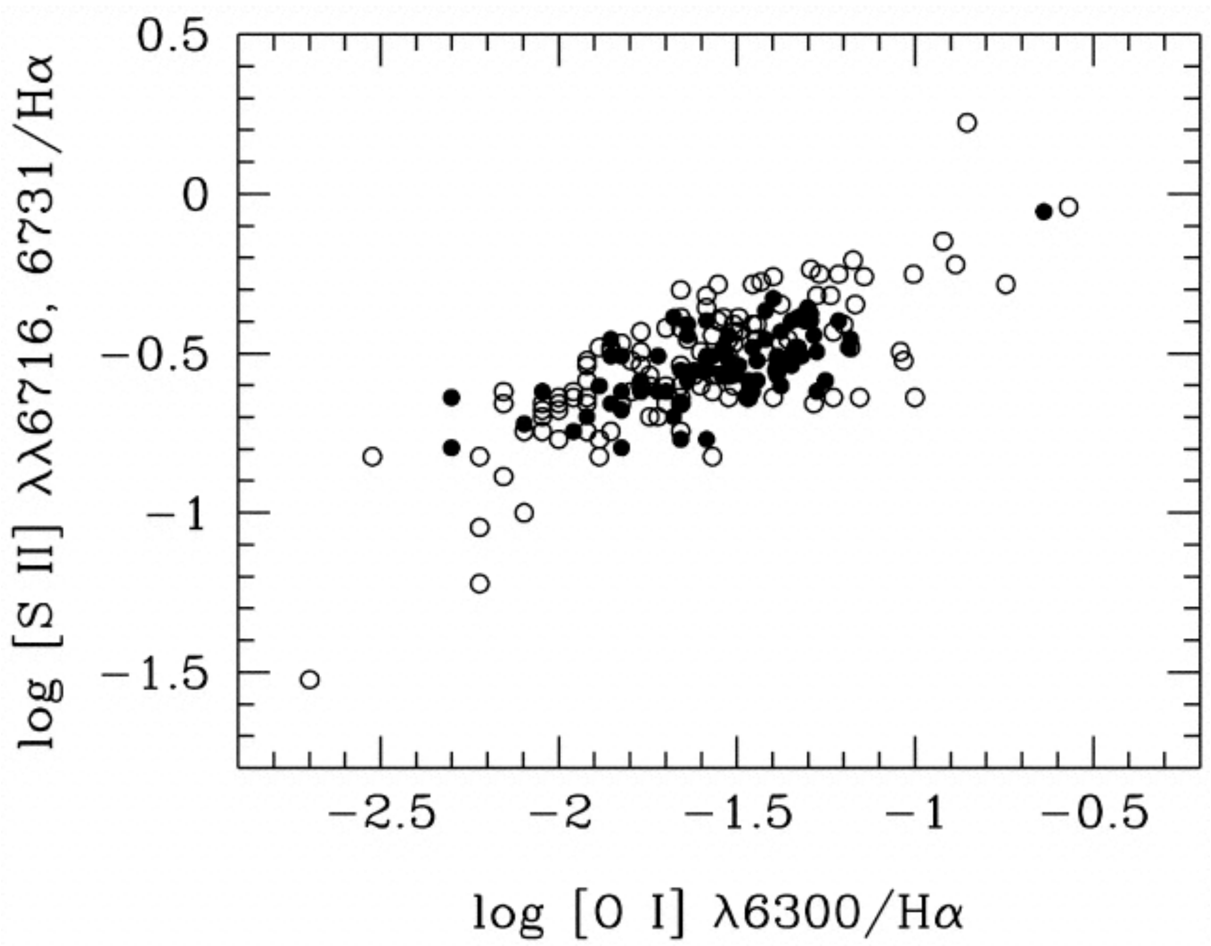
- Spectra of diffuse gas shows strong [N II] and [S II] but weak [O III] and [O I]
  - [N II]/Hα and [S II]/Hα measurements agree, but high [O I]/Hα does not
  - Diffuse emission: weak [O I] caused by matter-bound conditions
  - Nuclear H II regions: ionization-bound conditions
  - Unlikely that line-ratio anomalies occur because of diffuse ionized gas

Evidence for Shock Excitation

- Some H II nuclei in late-type hosts show strong [S II] and [O I] lines
- Look at 15 regions with [S II]/Hα≥0.5
  - Majority have highest [O I]/Hα ratios (median 0.054) - line ratios correspond
  - Hubble types: Scd to Sdm
  - Low luminosities: median $M^0_{B_T}$ of -19.4 mag
  - Closer than average: median distance 11.5 Mpc

Correlation between [O I] and [S II]

FIG 15



Possible Explanations

- Yes: Shocks from SNRs or stellar winds
  - could be tested by measuring a temperature-sensitive line like [O III] λ4363 or looking for SNRs
- Yes: Photoionization from hot stars
- No: Low metallicities expected in late-types, so dust alone is insufficient
- No: Presence of strong [O I] rules out diffuse ionized gas

IC 2574 - the ugly duckling

- Low excitation ([O III]/Hβ=0.23) peculiar for SABm galaxy
  - Miller & Hodge (1996): oxygen abundance only about 1/10 solar, consistent with galaxy type
- Miller & Hodge: 3 regions with [O III]/Hβ of 3 to 5
- Strengths of [N II] and [S II] in paper also appear enhanced by a factor of 2-3 from M&H

IC 2574 - continued

- Region “B” looks like primary peak “A” in its spectrum, three other spectra are similar to those of Miller & Hodge
    - A & B are 31” apart and their unusual spectra may be due to shocked plasma
    - 3 other regions, and those of Miller & Hodge, are enhanced in [S II] by mixture of photoionized and shocked gas
    - Weak [O III] and moderately strong [N II] and [S II] conform to collisional excitation in metal-poor medium. [O I] should be strong, but line is corrupted by night-sky emission

Oxygen and Nitrogen Abundances in IC 2574

- Using [O III] and [N II] ratios from this paper and comparing to Dopita et al. (1984) Fig. 10
  - A has O/H≈0.7 x 10^{-4} and O/N≈12
  - B has O/H≈1.5 x 10^{-4} and O/N≈24
- Using [N II] and [S II] ratios from this paper and comparing to Dopita et al. (1984) Fig. 8
  - A and B both have O/H≈0.2 x 10^{-4} and O/N≈5
  - If S/O increased by 2, O/H and O/N would be higher and abundances from diagnostic diagrams would be in agreement

Summary

- Similarities between H II nuclei and disk H II regions:
  - Similar Hα luminosities, electron densities, ionized hydrogen masses
- Differences between H II nuclei and disk H II regions:
  - Nuclei have higher oxygen abundance, higher internal extinction, smaller volume filling factors, smaller emission-line equivalent widths
- Nuclei have stronger low-ionization emission lines
  - Possibly due to: weak AGNs, hot stars with nebular conditions, shocks, dust grains

Summary continued

- Differences between Hubble types
  - Early-type have low excitation
  - Small # early-types have strong [N II] lines
  - Early-type have higher Hα luminosity - higher star formation rates - bars?
  - Early-type have higher reddening and higher electron densities
  - Minority of late-types have strong [S II] and [O I] emission - shock wave heating?

Evidence for a Massive, Young GC in NGC 1569

- Introduction
- Observations and Analysis
- The Dynamical Mass of the Cluster
- Conclusions

Introduction

- New class of star clusters: compact, highly luminous, young
- Could represent present-day analog of young globular clusters
- Appear in: amorphous galaxies, merging and interacting systems, circumnuclear star-forming regions, and other starburst systems
- Could have implications from large-scale star formation to galaxy formation/evolution

Evidence supporting young *globular* clusters

1. Quite compact: half-light radii of a few pc, similar the Galactic globular clusters
2. Brightest members have high luminosities: visual magnitude exceeding -14 to -15 (comparison R136 has M_v=-11.3)
3. Blue optical continuum colors and amount of UV radiation indicate ages from a few to 500 Myr

Models

- Population synthesis models: luminosities of clusters will fade to that of old globular clusters within 10-15 Gyr
  - Must be bound and dynamical evolution cannot dissolve them
- Shortness of timescale for expansion - gravitationally bound
- Masses derived - in range of Galactic globular clusters (GCs)

Measurement of Mass

- Globular cluster interpretation could be strengthened by direct cluster mass measurement
- With mass and luminosity, and a model of luminosity evolution - future mass-to-light ratio determination possible
  - Constrains stellar population, IMF of young clusters

Observations

- High dispersion spectra of NGC 1569-A, a bright cluster
- Wavelength range ~3900-6280 Å
- Aim: determine line-of-sight velocity dispersion of cluster
- Cluster age: ~10-20 Myr, measuring velocity dispersion more complicated

Spectral Analysis

- Arp & Sandage (1985): type A0 Iab
- Weak metal lines cannot be used because of other sources of line broadening
- Use region ~5000-6280 Å
- Spectrum dominated by supergiants near and redward of V band
- Light should come from cool (F-M) supergiants
- Early supergiants contribute, but are relatively featureless

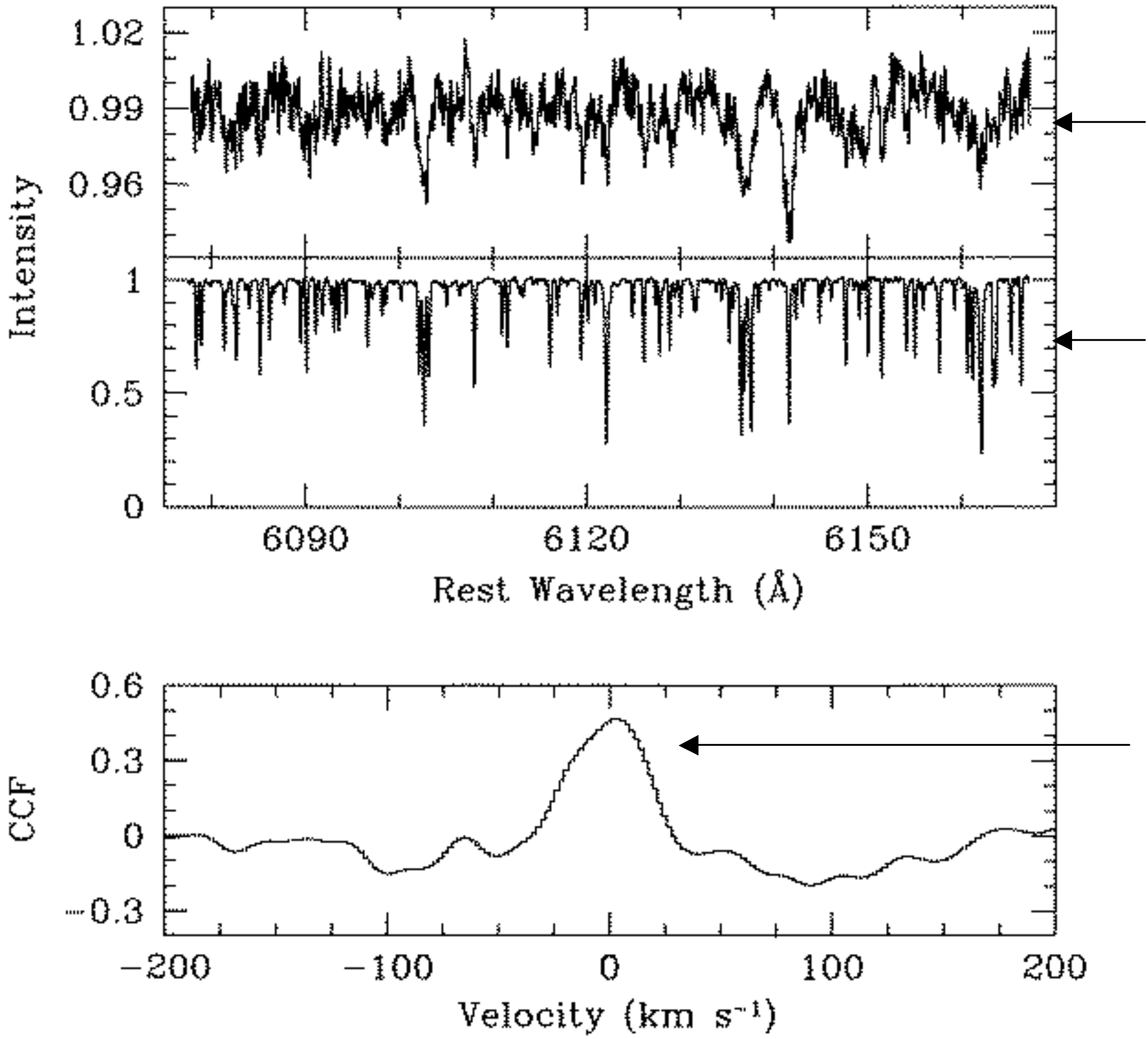
Comparison Stars

- Comparison with 177-A (A0 Supergiant)
  - Very few metal lines in 177-A spectrum
- Comparison with G to M giants and supergiants:
  - Nearly all features seen in NGC 1569-A are present
- Some flux also from early-B stars, but those stars also relatively featureless

Cross-Correlation

- Used HR 3422 (a G8 IV star) as a template to find velocity dispersion
- Subtracted from it in quadrature amount expected from intrinsic width of supergiants
- Applied cross-correlation from Tonry & Davis (1979) to spectral orders between 5000 and 6280 Å

FIG 1



NGC 1569-A

Template star

Cross-correlation
function - width of
main peak relates
to velocity dispersion

Results for Velocity Dispersion

- Avg velocity dispersion: 18.1 km/s, standard deviation: 1.1 km/s
- Assuming cool supergiants have intrinsic line widths of 9 km/s
- Line-of-sight velocity dispersion:
  - $\sigma_* = 15.7 \pm 1.5$ km/s
  - Near top end of distribution of velocity dispersions for Galactic GCs

Dynamical Mass of Cluster

- Assumptions: gravitationally bound, effective gravitational radius can be measured (all stars have equal masses, cluster spherically symmetric, velocity distribution isotropic)
- Virial theorem is used
- Half-light radius: 1.9 ± 0.2 pc (use as effective radius)
- $M=(3.3 \pm 0.5) \times 10^5\ M_\odot$

How Reliable is Mass Estimate?

- Virial theorem: bound and dynamically relaxed
  - First condition should be satisfied (compact - expansion timescale ~ 1 Myr)
  - Unlikely to be virialized if as massive as typical GC --- mass represents lower limit
- Equal mass assumption: oversimplification
  - Single-mass models underestimate total mass by 2x
- Use of spatially integrated spectra vs. radial velocities of individual stars
  - Former biases dispersion toward lower values

Half-Light Radius

- Used because it is not very sensitive to evolutionary or environmental effects
- Not well-know for NGC 1569-A and distance also uncertain
- Other papers show distance of 1.6-4.7 Mpc
- However, size of cluster enters linearly in virial equation - not as important as velocity dispersion

Comparison to GCs

- Mass in range (2-6) x 10^5 $M_\odot$, true mass could be higher than estimate
- GCs: average: 1.9 x 10^5 $M_\odot$ and median: 8.1 x 10^4 $M_\odot$
- Half-light radius: 1.9 pc (comparable to or slightly smaller than GCs)
- Mass density: 1.1 x 10^4 $M_\odot$ pc^{-3} at least as large as GC mass density

Mass-to-Light ratio

- Evolutionary synthesis calculations predict a 10 Myr cluster will fade 6-7 mag in 10-15 Gyr
- Current M_v=-14.1 mag, evolved cluster will have -7 to -8 mag
  - GC average M_v -7.3 mag
- Will have $M/L_v=2.5\text{-}6.3\ (M/L_v)_\odot$
  - GC typically have $0.7\text{-}2.9\ (M/L_v)_\odot$

Conclusions

- Found velocity dispersion using cross-correlation technique
  - $\sigma_* = 15.7 \pm 1.5$ km/s
- Used virial theorem and size estimate to find mass
  - $M = (3.3 \pm 0.5) \times 10^5 M_\odot$
- Derived mass, mass density, and mass-to-light ratio all indicate that cluster will evolve into fairly massive GC

THE END

- Looked at how H II regions and forming clusters give insight into stellar and galactic evolution