SECTION VII

LOW LEVEL ACTIVITY AND INTERMEDIATE OBJECTS

THE NATURE OF LINERS

Timothy M. Heckman
Astronomy Program
University of Maryland
College Park, MD 20785
U.S.A.

ABSTRACT: LINER´s (Low-Ionization Nuclear Emission-line Regions) are found in the majority of early-type (Sb or earlier) galaxies, and in some late-type and peculiar galaxies as well. Because they are so common but are not energized by normal stars, their nature is critical to our understanding of both the active galactic nucleus phenomenon and the evolution of normal galactic nuclei. After briefly reviewing the spectroscopic basis of the LINER classification, I summarize four alternative models for LINER´s: 1) LINER´s as "mini-Seyferts" in which the emission-line gas is photoionized by a more dilute version of the high-energy nonstellar continuum found in Seyfert nuclei. 2) LINER´s as accretion flows of cooling gas originating in the halos of galaxies and/or in the intra-cluster medium. 3) LINER´s as starburst-driven winds. 4) LINER´s as colliding, shock-heated galaxies. After reviewing the evidence, I conclude that it is very likely that several (and possibly all) of the above models are needed to account for the diverse properties of LINER´s. While LINER´s would then not have a single unified explanation, they would have a direct bearing on many issues in extragalactic astronomy.

1. INTRODUCTION

1.1 Emission-Lines as the Basis of a Classification System

One of the most characteristic, yet enigmatic properties of active galactic nuclei (AGN´s) is that they copiously produce radiation across nearly the entire electro-magnetic spectrum (see for example Martin Ward´s contribution to this volume). Insofar as the optical window spans only a single octave in frequency, why is so much observational and theoretical effort directed at understanding the properties of the optical emission-line spectra of galactic nuclei (see the recent review by Osterbrock and Mathews 1986)? Why should these spectra form the basis for a serious classification system for galactic nuclei? In part, the answer has to do with the "optical chauvinism" inevitably bred by the historical development of astronomy. However, there are much better

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reasons for the importance of the optical emission-line spectrum to AGN fanciers.

First, there is the practical matter of the efficiency, sensitivity, and cost-effectiveness of modern optical telescopes and their detectors: it is relatively easy to acquire good optical spectra of AGN's. This is not yet the case at other wavelengths.

Second, the optical emission-line spectrum contains a wealth of direct information concerning the physical and dynamical state of material in AGN's. The use of these diagnostics is greatly facilitated by the high quality of the readily-obtainable data.

Third, the optical spectrum contains a significant fraction of the strongest lines emitted by plasmas in the temperature range of 10E4 to 10E5 K (this is a very common temperature range for gas in AGN's for a variety of reasons - cf. Krolik, McKee, and Tarter 1981).

Finally, the relatively well-understood physics of the emission-line gas means that we can reliably use the properties of this gas to probe the nature of the primary energy source in AGN's.

1.2 The Spectroscopic Basis of the LINER Classification

The standard classification system for the optical emission-line spectra of AGN's is based on both emission-line ratios and on kinematic properties. Fortunately, the dynamical and physical states of gas in AGN's appear to be strongly related, so I will concentrate on line-ratios as the basis for the classification system. The first detailed consideration of how line-ratios could be best used to classify AGN's was in Baldwin, Phillips, and Terlevich (1981-hereafter BPT), who suggested the use of "two-color" diagrams (plotting pairs of line-ratios against one another). The diagnostic use of BPT diagrams has recently been refined by Veilleux and Osterbrock (1986). These diagrams will play an important role in the discussion to follow.

Three primary types of galactic nuclei can be distinguished on the basis of their optical emission-line spectra: HII regions, LINER's, and Seyferts. I have listed these in order of increasing "activity" (the increasing likelihood that something more exotic than normal stellar evolution is involved). The two ends of this activity sequence are reasonably well understood. HII region nuclei are clearly powered by newly-formed massive stars and bear close resemblance to ordinary extranuclear giant HII regions (see the reviews by Melnick and by Alloin in this volume). Seyfert nuclei almost certainly require a compact, massive power-source (Rees 1984; but see Terlevich and Melnick 1985 for an alternative viewpoint). In contrast, the nature of LINER's remains a subject of controversy, as I will discuss in detail below - see also the recent reviews by Keel (1985) and Heckman (1986).

The primary defining property of a LINER is the strength of the emission-lines produced by neutral and singly-ionized species (e.g. [OI]λ6300, [OII]λ3727, [NII]λ6583, [SII]λλ6716, 6731). This can be clearly seen in Table I and in the BPT diagrams in Figs. 1-4, but several specific points should be emphasized.

First, the [OI]λ6300 line is critically important in separating HII regions from both LINER's and Seyferts: it is strong in Seyferts and

TABLE I

Principal Reddening-Insensitive Emission-Line Ratios in LINER's

(1)	(2) [OIII]/Hβ	(3) [OI]/Hα	(4) [NII]/Hα	(5) [SII]/Hα
Observations:				
Bright Galaxies	0.1±0.4	-0.6±0.5	0.1±0.4	0.0±0.4
Accretion Flows	0.0±0.3	-0.4±0.3	0.0±0.3	0.0±0.4
M82 Nebula	-0.1	-1.1	-0.4	-0.4
NGC253 Nebula	-0.5	?	0.0	-0.3
NGC6240 Nebula	0.2	-0.6	0.0	-0.1
Arp220 Nebula	0.2	-0.7	0.0	-0.2
Far-IR Galaxies	0.2±0.4	-1.0±0.5	-0.2±0.3	-0.3±0.3
Models:				
FN Power-Law	0.2	-0.4	0.1	0.1
HS X-ray	0.3	-0.1	0.0	?
SM Shock	0.4	-0.8	-0.2	0.0
TM Warmers	0.2	-0.4	0.0	0.1
ED 56000K Star	0.2	-0.9	-0.1	?

Notes to Table 1.

Col. 1) The "Bright Galaxies" sample comes from the various spectroscopic surveys of the nuclei of bright galaxies (Heckman, Balick, and Crane 1980; Heckman 1980; Stauffer 1982a, b; Keel 1983a, b: Phillips et al. 1986). The "Accretion Flows" sample consists of cluster-dominant giant ellipticals/cD's thought to be immersed in a cooling accretion flow (Hu, Cowie, and Wang 1985 and references therein; Ford and Butcher 1979; Fabian et al. 1985; Costero and Osterbrock 1977). Data for M82, NGC253, NGC6240, and Arp220 come from MHvB and HAM. The "Far-IR Galaxies" are described in section 2.4.2 and in detail in HAM. The "FN Power Law" model is taken from Ferland and Netzer (1983) and is for solar abundance gas photoionized by a power-law continuum source and having log U=-3.7. The "HS X-ray" model is taken from Halpern and Steiner (1983) and represents solar abundance gas heated by a broken power-law continuum source that has been filtered through thick clouds that absorb 0.97 of the UV and sub-kev X-ray photons, but few of the harder ones. The "SM Shock" model is from Shull and McKee (1979) for a 90 km/sec shock with solar metallicity (average of their models D and E). The "TM Warmers" model (Terlevich and Melnick 1985) is for solar abundance gas photoionized by a cluster of Warmers (massive stars undergoing extreme mass-loss) with log U=-3.7. The "ED 56000K Star" model is from Evans and Dopita (1985) for solar abundance gas photoionized by an extreme O star with an effective temperature of 56,000 K and having a low ionization parameter (log U=-3.5).

Cols. 2-5) The logarithms of the [OIII]λ5007/Hβ, [OI]λ6300/Hα, [NII]λ6583/Hα, and [SII]λλ6716, 6731/Hα flux ratios. The typical ranges spanned by the various classes of objects are indicated.

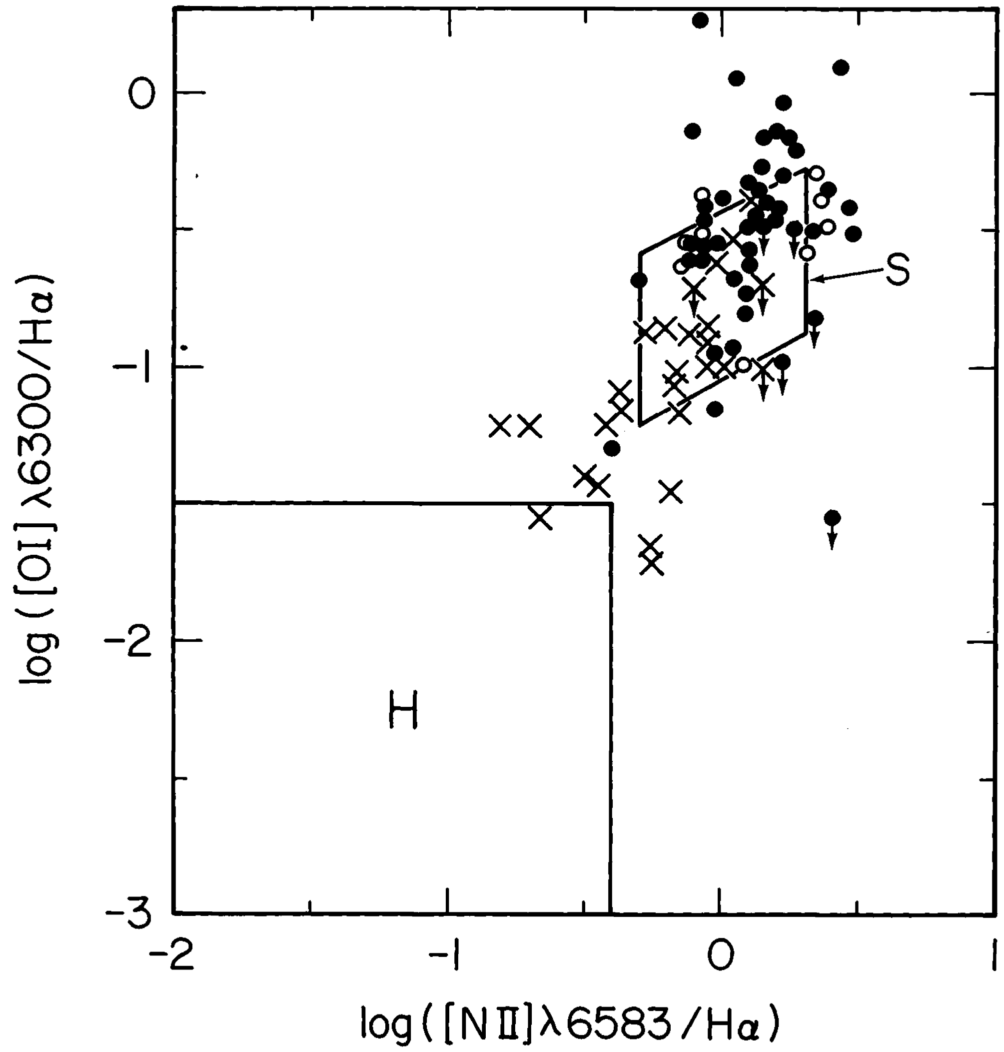

Fig. 1) The log of the flux ratio of the [OI]λ6300 and Hα lines is plotted vs. the log of the flux ratio of the [NII]λ6583 and Hα lines for three samples of galaxies with LINER spectra (for details see the notes of Table I). The solid dots are nuclei observed in surveys of bright galaxies (the "Bright Galaxy" sample). The hollow dots are giant E/cD galaxies in accretion flows (the "Accretion Flow" sample). The crosses are strong infrared galaxies (M82, NGC253, NGC6240, Arp220, and the "Far-IR Galaxy" sample). The locations of Seyfert nuclei and HII regions are indicated schematically by the boxes labeled "S" and "H" respectively. Note that about half of the infrared galaxies have spectra that strongly resemble the "Bright Galaxy" and "Accretion Flow" LINER´s, while the other half are intermediate between LINER´s and low-excitation HII regions.

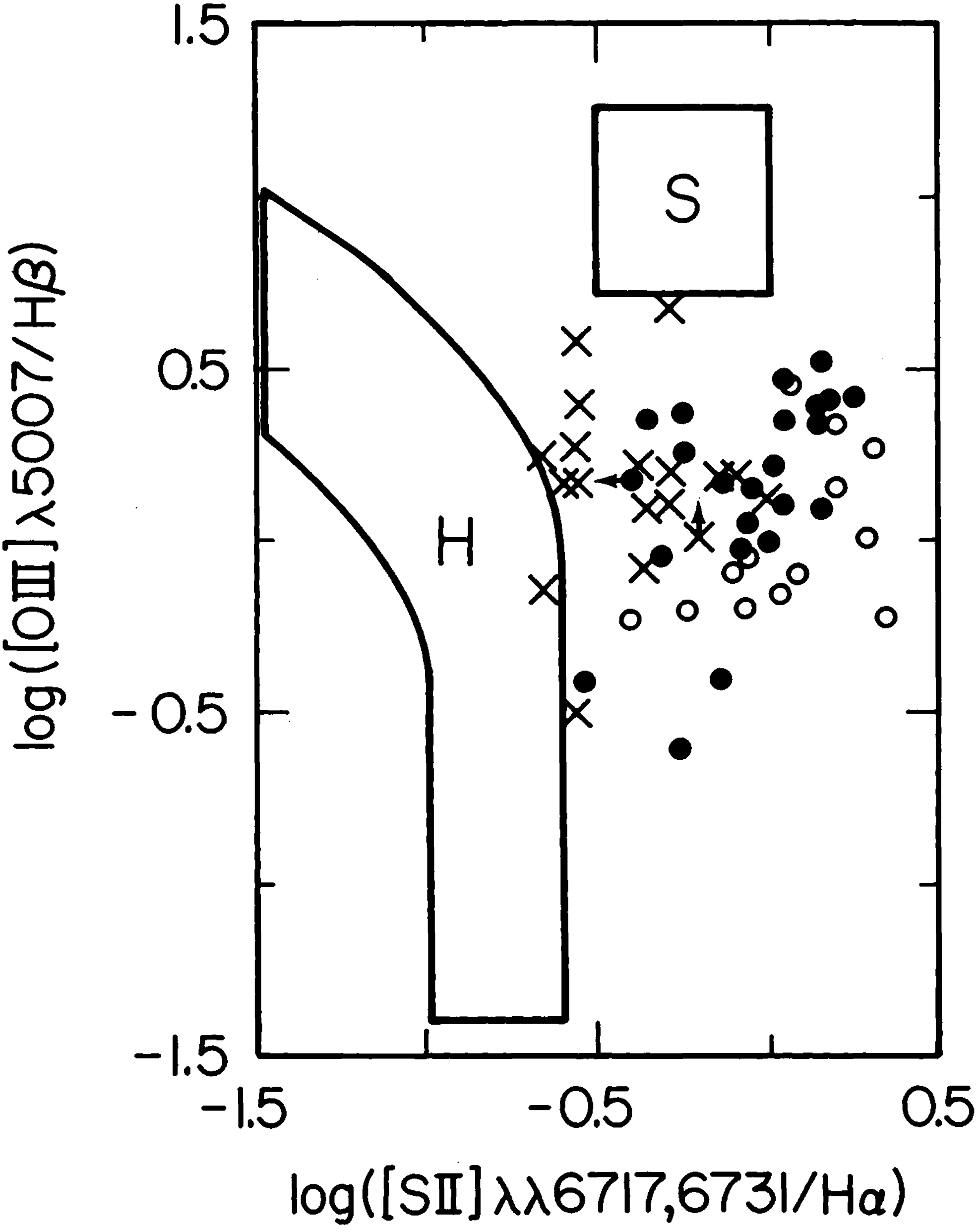

Fig. 2) The log of the flux ratio of the [OIII]λ5007 and Hβ lines is plotted vs. the log of the flux ratio of the [SII]λλ6716, 6731 and Hα lines. The various symbols and boxes have the same meaning as in Fig. 1.

LINER´s, but weak in HII regions. The latter can be understood because an HII region has a sharp boundary between the warm, ionized gas within the Stromgren sphere and the cold, neutral gas outside (there is very little warm, neutral gas where the collisionally-excited [OI]λ6300 line is produced). This sharp boundary is the result of the low energies of the typical ionizing photons produced by OB stars (such photons can not penetrate very far into the cold, neutral gas). In contrast, Seyfert nuclei produce ample amounts of high energy photons that can penetrate deeply into the neutral gas, creating an extended zone of mostly neutral but warm gas that is a strong source of [OI]λ6300 emission. In photoionization models of LINER´s, the strength of the [OI]λ6300 line can be understood in a similar way. In shock models for LINER´s, the strong [OI] line is the result of the very extended recombination zone behind the shock.

Second, the principle difference between LINER´s and Seyferts is the weakness of high ionization lines (e.g. [OIII]λ5007, [NeV]λ3426) in the former. As discussed below, in photoionization models of LINER´s this difference is caused by a more diffuse ionization source, resulting in a lower state of ionization equilibrium. Alternatively, the difference could reflect a fundamentally different ionization source in LINER´s vs. Seyferts (shocks vs. photoionization).

1.3 Motivation: Why Study LINER´s?

LINER´s are found in the majority of the nuclei of early-type (Sb and earlier) galaxies, and also in many later-type and peculiar galaxies - see the surveys of Heckman (1980), Stauffer (1982a), Keel (1983a), and Phillips et al. (1986). If only because LINER´s are so common, it is clearly important to understand them. Much of the attention paid to LINER´s is concerned with whether or not they are truly "active" nuclei powered by a compact, massive object. If LINER´s are true AGN´s, then low-level nuclear activity must be nearly ubiquitous in early-type galaxies. This would be very important for many reasons - Heckman (1986); Filippenko and Sargent (1985). Alternatively, and of potentially equal interest, LINER´s may involve some significant and qualitatively unique processes not evident in either Seyfert or HII region nuclei.

2. FOUR POSSIBLE CLASSES OF LINER´S

2.1 Introduction

In this section, I will explore various astrophysically plausible models for LINER´s and will summarize the relevant evidence. This approach is motivated by the suspicion that LINER´s may not have a single unified explanation, but may instead be a variety of superficially similar but physically distinct phenomena. I will try to be deliberately provocative in order to help potentially important ideas from being prematurely discarded.

2.2 LINER´s as Mini-Seyferts

2.2.1 The Model.

The most popular model for LINER´s is one in which they are photoionized by the same kind of energetic continuum source found in Seyfert nuclei (e.g. Halpern and Steiner 1983; Ferland and Netzer 1983; Stasinska 1984; Binette 1985; Pequignot 1984). The only significant difference between LINER´s and Seyferts in this model is a quantitative one: the emission-line clouds in LINER´s are irradiated by a more diffuse ionizing photon bath. More quantitatively, the "ionization parameter"

$$U = Q/(4\pi r^{**}2\ nc)$$

(where Q is the number flux of ionizing photons produced by a central source a distance r from a cloud with an electron density n) is about a factor of ten lower in LINER´s than in Seyferts. Note that U is just the ratio of ionizing photons to free electrons in the emission-line clouds. Elementary considerations of photoionization equilibrium show that low U in a LINER would lead directly to gas in a low state of ionization, as is observed.

2.2.2 The Evidence.

i) The photoionization models of LINER´s fit the observed emission-line spectra quite well using roughly solar abundances and relatively few free parameters (see Figs. 1-4 and Table I).

ii) It is attractive to link LINER´s directly to Seyferts because of the overall similarity/continuity between the two classes. The boundary between LINER´s and Seyferts in BPT diagrams is rather arbitrarily drawn, and there is also a considerable overlap in luminosity between them (e.g. Heckman 1980; Veilleux and Osterbrock 1986). Both are preferentially found in the nuclei of galaxies of early Hubble type (see Balick and Heckman 1982 and references therein). The kinematics of the emission-line gas is similar in LINER´s and Seyferts: in addition to a Narrow-Line Region in which line-widths are typically 400-500 km/sec in both classes (Wilson and Heckman 1985; Whittle 1985), both also commonly exhibit a Broad-Line Region with line-widths of many thousands of km/sec (see Filippenko and Sargent 1985 and references therein).

iii) Some LINER´s exhibit moderately strong X-ray, infrared, and/or featureless optical/near-UV continuum emission. These could signal the presence of the Seyfert-like energetic continuum source required by the photoionization models (e.g. Halpern and Steiner 1983; Halpern and Filippenko 1984; Filippenko 1985; Goodrich and Keel 1986; Lawrence et al. 1985). However, in other LINER´s, the upper limit to the observed strength of such a continuum source is significantly below the model´s requirements (Fosbury et al. 1981; Goodrich and Keel 1986). Moreover, an association between LINER´s and X-ray or infrared emission is predicted by the competing models for LINER´s as well (see below).

iv) Many LINER´s are associated with suggestive signs of a compact

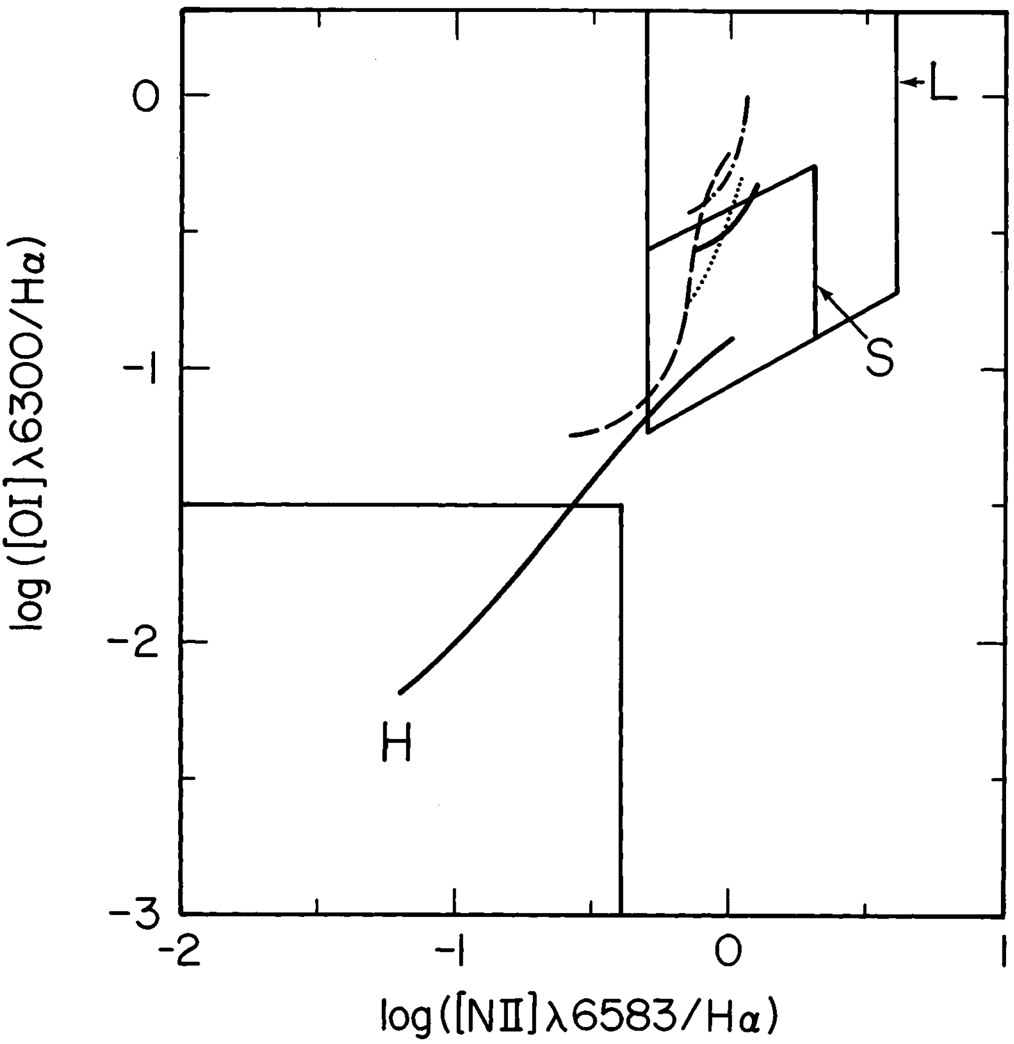

Fig. 3) The [NII]λ6583/Hα and [OI]λ6300/Hα logarithmic flux ratios are plotted against one another for models of LINER's (for details see the notes to Table I). The long solid line is for the "ED 56000K Hot Star" model with log U running from -1.5 (bottom) to -3.5 (top). The short solid line is for the "FN Power Law" model with log U running from -3 (bottom) to -4 (top). The dashed line is the "SM Shock" model with the shock velocity increasing from 80 to 130 km/sec from bottom to top. The dotted line is the "TM Warmer" model with log U running from -3 (bottom) to -4 (top). The dot/dash line is the "HS X-ray" model with the covering factor increasing from 0.90 (bottom) to 0.98 (top). The schematic location of LINER's (box labeled "L") is based on the "Bright Galaxy" and "Accretion Flow" samples (solid and hollow dots in Fig. 1).

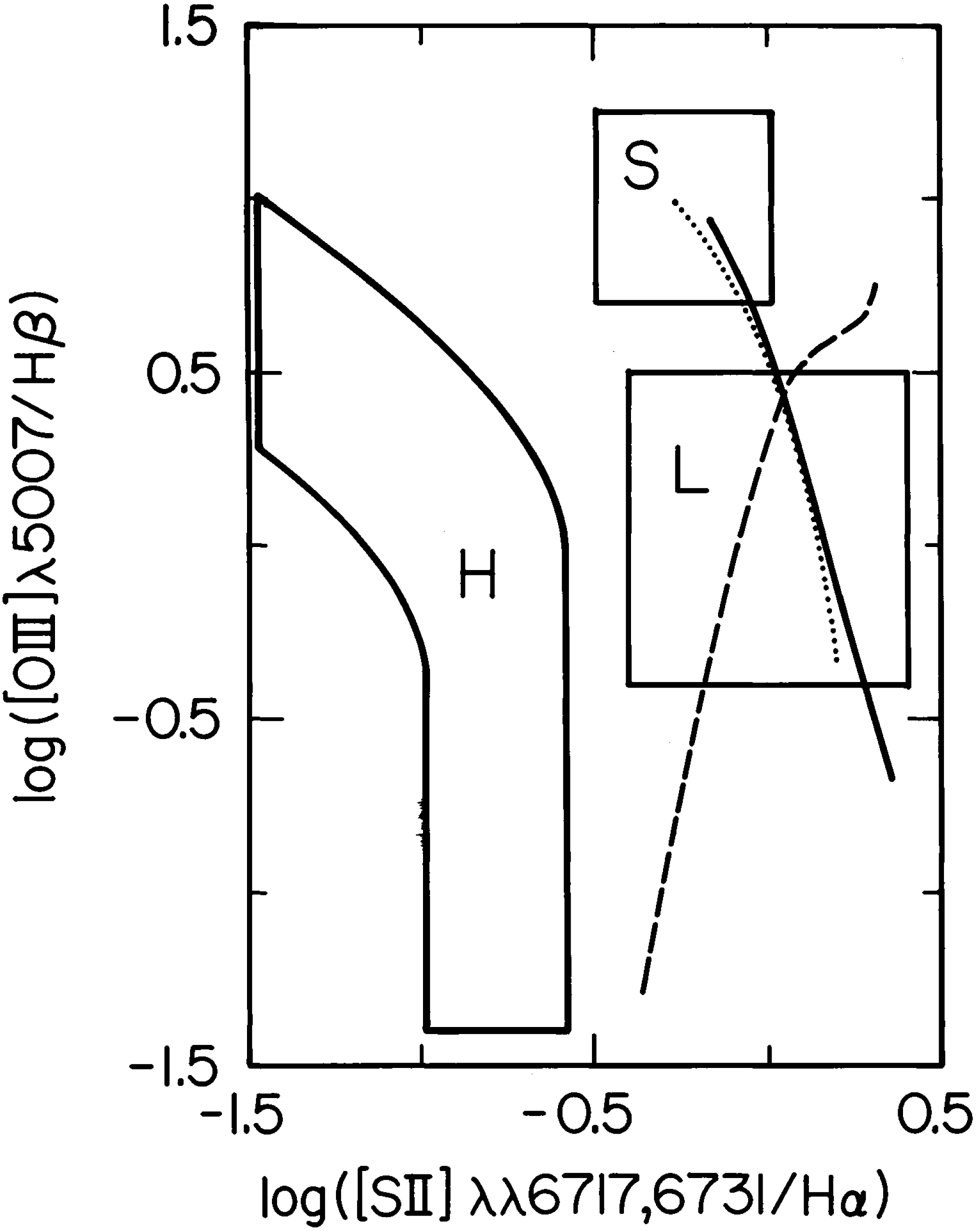

Fig. 4) As in Fig. 3, but for the [OIII]λ5007/Hβ and [SII]λλ6716, 6731/Hα logarithmic flux ratios. The "HS X-ray" and "ED 56000K Hot Star" models are not shown since the predicted strength of the [SII] lines was not published by these authors.

active nucleus (a "monster"). I have already mentioned the presence of a Broad-Line Region, X-ray emission, infrared emission, and a "featureless" component in the optical/near-UV continuum in some LINER´s. LINER´s are also statistically linked to the presence of compact, flat-spectrum radio cores in galaxies (O´Connell and Dressel 1978; Heckman 1980). Much more powerful versions of such radio sources are common in radio galaxies and radio-loud quasars (see Kellermann´s review in this volume). Also, many radio galaxies and some BL Lacs have weak LINER spectra.

v) Most evidence now suggests that the electron temperatures in the O++ zone in LINER´s may be consistent with photoionization models, contrary to the earlier reports (Fosbury et al. 1978; Koski and Osterbrock 1976) that the temperatures were too high. Keel and Miller (1983) and Rose and Tripicco (1984) have emphasized the extreme practical difficulty in accurately measuring the temperature-sensitive strength of the weak [OIII]λ4363 line in the presence of the complex stellar absorption-line spectrum that underlies the line. Filippenko and Halpern (1984), Filippenko (1985), and Carswell et al. (1985) have shown that the great strength of the [OIII]λ4363 line in some LINER´s is likely to indicate high densities rather than high temperatures.

2.3 Class II: LINER´s as Cooling Accretion Flows

2.3.1 The Model.

As suggested by Cowie and Binney (1977) and Fabian and Nulsen (1977), the X-ray emitting gas in the centers of rich clusters of galaxies can have a cooling time that is shorter than the age of the universe, and it should therefore cool and flow quasi-hydrostatically onto the giant elliptical/cD galaxy at the bottom of the cluster potential well. As the temperature drops below about few*10E5 K, optical/UV line radiation is the dominant coolant, and the accreting gas should be a source of LINER-type emission-lines (e.g. Mathews and Bregman 1978; Kent and Sargent 1979). Nebulae with LINER spectra (see Figs. 1-4 and Table I) are now known to be commonly associated with dominant galaxies in X-ray clusters (e.g. Heckman 1981; Cowie et al. 1983; Hu, Cowie, and Wang 1985).

Subsequently, the cooling flow model was generalized to encompass accretion flows in poor groups of galaxies (e.g. Canizares, Stewart, and Fabian 1983) and in the halos of individual giant elliptical galaxies (Biermann and Kronberg 1983; Nulsen, Stewart, and Fabian 1984; Sarazin 1986a). The models for the production of the emission-line filaments were also refined to include the effects of repressurizing shocks driven into the isochorically cooling, dense filaments by the hot surrounding X-ray gas (Cowie, Fabian, and Nulsen 1980). Fabian et al. (1986) suggest that X-ray heating of the emission-line clouds by the surrounding hot gas may also be energetically important. They also speculate that mini-cooling flows may offer a general model for LINER´s in ordinary galaxies. For more details on cooling flows, see the recent reviews by Fabian, Nulsen, and Canizares (1984) and Sarazin (1986b).

2.3.2 The Evidence.

i) Models of gas heated by ~ 100 km/sec shocks (e.g. Dopita 1977; Shull and McKee 1979; Raymond 1979; Binette, Dopita, and Tuohy 1985) provide good fits to observed LINER spectra (Table I and Figs. 1-4). Indeed, shock heating was the early favorite for LINER's in general (Fosbury et al. 1978; Heckman 1980). For the proper range in ionization parameter, X-ray heating could also produce good LINER spectra (see the Halpern and Steiner models in Fig. 3 and Table I).

ii) Hu, Cowie, and Wang (1985) have found a strong relationship between the brightness of the emission-line gas and the density of the X-ray emitting gas in the centers of cluster cooling flows. Indeed, the relationship implies that bright LINER-type nebulae occur only in the galaxies where the X-ray gas has a derived cooling time shorter than the Hubble time - exactly as expected in the model.

iii) Phillips et al. (1986) find that the presence of a LINER in a normal elliptical or SO galaxy is correlated with the presence of detectable X-ray emission. This is particularly interesting because Forman, Jones, and Tucker (1985) interpret such X-ray sources as hot gaseous halos, which (as summarized above) may be undergoing cooling flows.

iv) The relation between the LINER phenomenon and nonthermal radio emission noted in section 2.2.2 above could be understood in the cooling flow model as well: the presence of a cooling flow produces a LINER spectrum, fuels the central engine (powering the radio jets), and confines the radio plasma so that it loses energy radiatively and not through adiabatic expansion.

In summary, it seems well established that cooling flows occur in the centers of many rich clusters and in some (most?) luminous elliptical and SO galaxies. The cluster flows are associated with LINER-type spectra. The degree to which this model can be generalized to the LINER's commonly found in the nuclei of ordinary early-type galaxies is less clear.

2.4 Class III: LINER's as Starburst-Driven Winds

2.4.1 The Model.

Chevalier and Clegg (1985-hereafter CC) have recently considered the consequences of the high star-formation rate (and associated high supernova rate) in the circum-nuclear (100-1000 pc) molecular disk in the proto-typical infrared starburst galaxy M82. CC hypothesize that the kinetic energy of the supernova ejecta are efficiently thermalized via shocks, and form a cavity of very hot gas at the center of the molecular disk. This hot gas can then expand outward along the disk's minor axis as a fast (several thousand km/sec) wind. They predict that the wind material itself is a negligible source of radiation, but that ambient clouds are shock-heated by the wind to produce the observed X-ray/emission-line nebula. The emission-line nebula should therefore have a LINER spectrum.

Heckman, Armus, and Miley (1986-hereafter HAM) and McCarthy, Heckman, and van Breugel (1986-hereafter MHvB) have presented new observations that significantly strengthen the case for starburst-driven winds as a common feature of strong infrared galaxies (as summarized below). They also suggest that ionizing photons produced in the circumnuclear starburst could escape along the wind's flow axis and (like shocks) play an important role in the ionization of the emission-line nebulae. A LINER spectrum would result if the photoionization source were sufficiently hot and the radiation field were sufficiently dilute (low U). As seen in Figs. 1-4 and Table I, a starburst dominated by "Warmers" (Terlevich and Melnick 1985) could work, but even 0 stars with T=56,000 K should suffice if U=few*10E-4 (Evans and Dopita 1985).

2.4.2 The Evidence.

M82) We (MHvB) have recently summarized the case for a starburst-driven wind in M82. The high supernova rate required to drive the wind is demonstrated by the population of time-variable compact nonthermal radio sources in M82 (Kronberg, Biermann, and Schwab 1985). The nozzle for the wind is evident in recent high resolution CO maps of a molecular annulus coincident with the region of the starburst (Nakai 1984). The bipolar nature of the wind is clear: the emission-line and cospatial X-ray nebulae (Watson, Stanger, and Griffiths 1984) are oriented perpendicular to the molecular annulus and largescale galaxy disk. Recent Fabry-Perot observations show strong evidence for high speed outflow in the nebula (A. S. Wilson, private communication; see also Axon and Taylor 1978). Our new data confirm that the pressures in the emission-line nebula drop smoothly with radius, in excellent quantitative agreement with the CC wind model (Fig. 5). Finally, our spectra also show that the M82 nebula has a LINER spectrum (Figs. 1-4 and Table I).

NGC253) The available data for this infrared starburst galaxy are less detailed than for M82, but the resemblance so far is striking. We (MHvB) find a region of gas with a LINER spectrum (Figs. 1-4 and Table I) along the minor axis of the galaxy and coincident with the X-ray nebula discovered by Fabbiano and Trinchieri 1984). This gas appears to be flowing out (e.g. Ulrich 1978) of a circumnuclear molecular disk undergoing intense star formation (e.g. Scoville et al. 1985).

Arp220/NGC6240) These are the two best-studied examples of very powerful infrared galaxies (~ 10E12 L[sun]), and appear to be powered by some combination of star formation and an AGN (Rieke et al. 1985; Becklin 1986; Depoy, Becklin, and Wynn-Williams 1986). HAM have discovered that both galaxies have large (tens of kpc) and morphologically spectacular (bubbles, filaments, arcs, etc.) emission-line nebulae (Figs. 6 and 7) with LINER spectra (see Figs. 1-4 and Table I). Thus, the nebulae bear a strong qualitative resemblance to those in M82 and NGC253. HAM suggest that they are larger versions of the same general phenomenon.

IRAS Survey) HAM also present spectra of a sample of 20 galaxies identified with very powerful infrared (IRAS) sources having the same far-infrared spectral energy distribution as M82, Arp220, and NGC6240. The emission-line spectra of these galaxies are very similar to that of the M82 nebula: about half are LINER's and the others appear intermediate between LINER's and low-excitation HII regions (Figs. 1-4

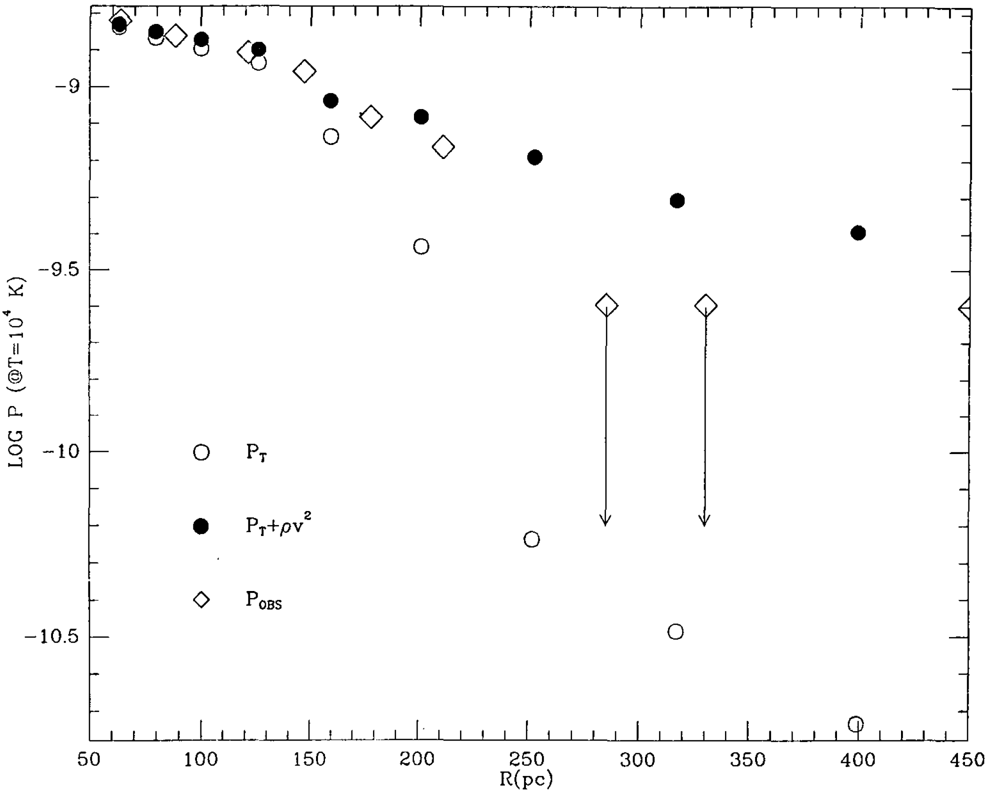

Fig. 5) The observed radial dependence of the gas pressure in the M82 nebula (=2nkT where n is the electron density derived from the ratio of the [SII]λ6716/λ6731 lines and T is taken to be 10000 K) is plotted along with the predicted thermal pressure and total (thermal plus ram) pressure in the wind model of Chevalier and Clegg (1985). The plotted wind model pressures are a factor of five below the maximum allowed by the model. See MHvB for details.

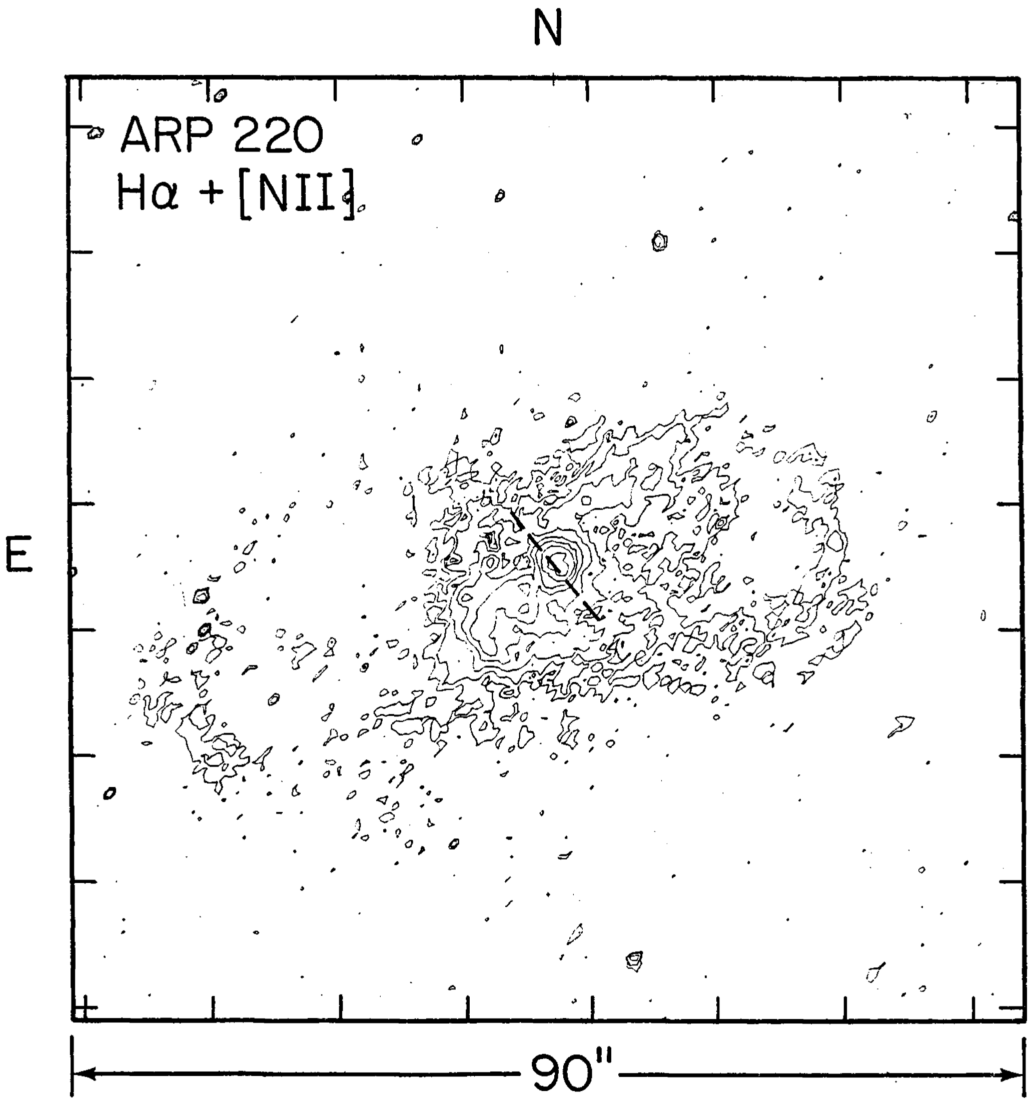

Fig. 6) Contour plot of the continuum-subtracted Hα image of Arp220. The first contour is at a surface brightness of 3.4E-17 ergs/(cm**2 sec arcsec**2) and each subsequent contour is at a factor of two higher brightness. The dashed diagonal line represents the orientation of the central dust-lane. See HAM.

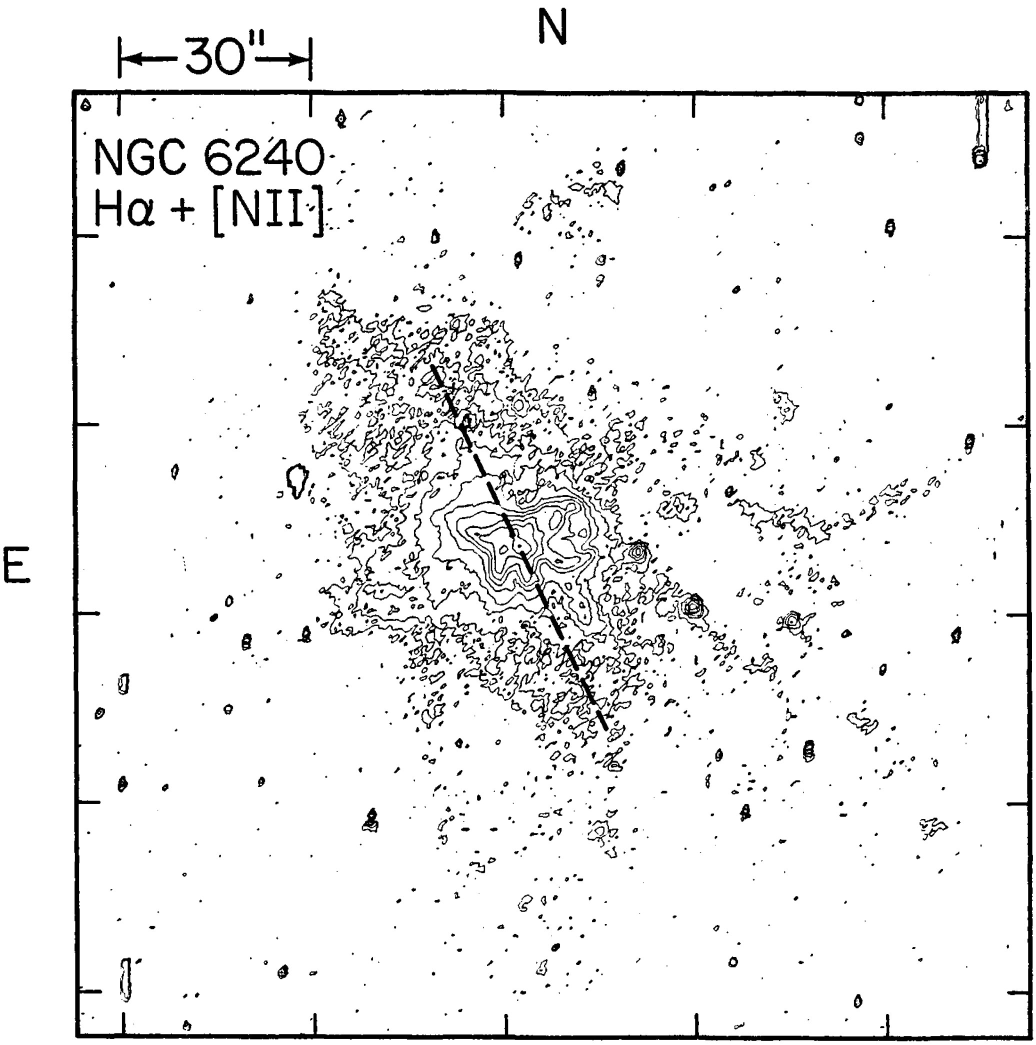

Fig. 7) Contour plot of the continuum-subtracted Hα image of NGC6240. The first contour is at a surface brightness of 6.6E-17 ergs/(cm**2 sec arcsec**2) and each subsequent contour is at a factor of two higher brightness. The dashed diagonal line represents the orientation of the galaxy's major axis. See HAM.

and Table I). The emission-line gas is also spatially-extended (>10 kpc) in some (and possibly most) of them. While these data are limited, the fact that large LINER-like nebulae are commonly associated with powerful infrared galaxies suggests that the starburst-driven winds are a quite general phenomenon.

2.5 Class IV: LINER´s as Galaxy Collisions

As I have emphasized, models of shock-heated gas provide quite acceptable fits to the observed spectra of LINER´s (see Table I and Figs. 1-4). One of the most natural situations in which widespread shocks should occur is when two galaxies collide or merge. This could occur in a violent and spectacular fashion if two gas-rich galaxies collided almost head-on. However, a low-level LINER could also result from cloud-cloud collisions as gas captured by a galaxy slowly and dissapatively settled into a disk (e.g. Gunn 1979; Lake and Norman 1983).

Fosbury and Wall (1979) first suggested that the LINER in the highly distorted galaxy NGC6240 (see above) might be directly excited by the collision of two gas-rich galaxies. Later, Phillips (1981) proposed that the diffuse LINER nebula in the well-known peculiar galaxy NGC5128=Centaurus A could have a similar origin. Most recently, McCarthy et al. (1986) speculate that LINER-type gas associated with dust lanes in a number of ellipticals (including NGC5128) might be captured material shock-heated in cloud-cloud collisions during disk formation. Finally, Harwit (1986) has recently developed a "collision" model to account for the distorted optical morphologies of many powerful infrared galaxies. He proposes that the optical and UV emission produced in shocks in a head-on galaxy collision is efficiently reprocessed by dust and emerges as strong far-infrared radiation. This idea is intriguing because, as we have seen in section 2.4.2, nebulae with LINER spectra are common in strong far-infrared galaxies. For such objects, the collisions model may offer a viable alternative to the wind model discussed above.

3. CONCLUSIONS

The evidence summarized above strongly suggests (to me at least) that the objects called LINER´s are not a single class, but are instead several superficially similar, but physically distinct classes. Despite the praises I sang in section 1.1, this becomes evident only if we broaden our observational and theoretical perspective beyond the confines of optical emission-line spectroscopy.

Having reached the qualitative conclusion that there are probably several different kind of LINER´s, I will largely skirt the much more difficult (but critically important) quantitative issue as to the relative fraction of LINER´s falling into the various classes (I do so on the grounds that the available data are inadequate). I emphasize however that the great majority of LINER´s in the local universe are those discovered in unbiased spectroscopic surveys of optically-bright galaxies. These LINER´s are not usually strong far-infrared sources, rarely show any other evidence for recent/on-going nuclear star formation, and are mostly morphologically normal galaxies. The "winds" or "collisions" models seem less likely to be generally appropriate, and so my best guess is that either the mini-Seyfert model or the mini-accretion-flow model could explain most LINER´s. These two models seem to account most naturally for the preferential occurrence of LINER´s in luminous, early-type galaxies. First, we know that Seyfert and radio galaxies are also preferentially luminous, early-type galaxies (Balick and Heckman 1982 and references therein), so it is likely that this kind of galaxy will be the preferred site of low-level nuclear activity (mini-Seyferts). Second, only for this kind of galaxy is there observational evidence for an X-ray-emitting gaseous reservoir to fuel an accretion flow.

The existence of several different classes of LINER´s may be disquieting to those who put great scientific stock in Occam´s Razor. However, it does mean that LINER´s touch many of the most important unresolved questions in extragalactic astronomy: How common are AGN´s? Where are all the "dead" QSO´s? How are AGN´s fueled? What is the relationship between star formation and "genuine" nuclear activity? How do the interstellar and intergalactic media evolve dynamically, thermally, and chemically? What powers luminous infrared galaxies? What do galaxies in formation look like and how might they interact with their environments? How often do galaxy mergers/collisions occur and what are their consequences for galaxy evolution? Clearly, the study of LINER´s and their associated phenomena is going to be with us for a long time!

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DISCUSSION

PISMIS: Could you comment on the radio properties of LINER's. How is the radio continuum? Thermal, nonthermal or a mixture of them? Is polarization observed in the radio range or in the optical one?

HECKMAN: The radio properties of LINER's are very diverse. Most of the LINER's found in bright, nearby galaxies are associated with rather weak compact radio sources which are probably related to the much more powerful sources seen in quasars and radio galaxies. Some LINER's are found in the nuclei of powerful radio galaxies (like M87 for example). I know of no thermal radio sources in LINER's. Very little is presently known about the polarimetric properties of LINER's.

TUTUKOV: Four years ago we developed a one dimensional numerical model of starformation in galactic nuclei (Loose, Krügel and Tutukov, 1982, Astron.Ap., 105, 342). We succeded to describe bursts of star formation which explain quite well bursts in NGC 253 and M82 that you discussed (Krügel et al., 1983, Astron. Ap. 124, 89). It is shown that bursts are possible only if the minimal mass of the initial mass function is above one solar mass. This model may be successfully used to interpret observational data on several types of activity of galactic nuclei.

RODRIGUEZ ESPINOSA: Is there any difference in the far-infrared emission of the three classes of liners that you have described? I presume that if class III is starburst-driven this class will show stronger FIR emission than the rest. Is that the case?

HECKMAN: Yes, it is true that the class III LINER's are all strong FIR sources, but we used strong FIR emission to locate them in the first place, so this is somewhat circular evidence. More work will be required to sort out the detailed relationship between FIR emission and the various LINER classes.

FILIPPENKO: A crucial test of shock heating in your class II and class III objects would be to measure [OIII]λ4363 at distances of a few kpc from the nucleus. Since the gas densities in those regions are probably low, a high intensity for [OIII]λ4363 would indicate a high temperature, as required by shock models.

HECKMAN: I agree completely. Such measurements should be attempted, but will be difficult because of the low surface brightnesses of the gas.

MELNICK: NGC 1068 has many of the properties of your type III liners (i.e.CO-rings, starburst(s) in the centre, extended optical and radio emission...). Do you think some Seyfert galaxies may also be explained by your model?

HECKMAN: It is quite possible that those Seyferts showing strong evidence for kpc-scale high luminosity starbursts (like NGC 1068 and NGC 7469) will also have "superwinds" like those we hypothesize for Arp 220, etc. In general it is more difficult to see morphological evidence for these "superwinds" when the galaxy is seen at small inclination (as is the case for the above Seyferts).

OSTERBROCK: I think the concept that the objects originally called "LINER's " may be of three or four different physical classes is a very good one. Would you not agree that for galaxies close enough to be resolved, the Class II and Class III LINERs you described would be expected to have the morphological characteristic of having extended areas of emission-line gas, while the Class I objects would be similar to Seyfert 2 galaxies in having only small ("semistellar") regions?

HECKMAN: I think that you are probably correct. In fact, the evidence we have gathered thus far on our candidates for superwinds does suggest that LINER - like emission-line nebulae $\gtrsim$10kpc in size may be common in these "LINER class III" galaxies. The available data on cooling-flow LINER's (gathered by Cowie, Hu, myself, and others) also imply that these "class II" LINER's are often large in linear size ($\gtrsim$10kpc). Clearly, more data on well-defined samples of LINER's are needed to quantify the differences in linear size between the various classes that I have proposed.

Elaine Sadler's low level activity was very high level astronomy