I. Introduction

The phenomenon of LINERs has received much attention in recent years, and their classification is still under development. LINERs are a class of active galactic nuclei (AGNs) that are characterized by a low level of ionization of the interstellar gas. This is in contrast to Seyfert galaxies, which have a higher ionization state and thus exhibit strong emission lines. LINERs are considered to be a bridge between normal galaxies and Seyfert galaxies, and their study can provide important insights into the nature of AGN activity.

Abstract

Transition nuclei and the nature of NGC 4569

In this paper, we present new observations of the transition nuclei in NGC 4569, and we discuss the implications for the classification of this galaxy. Our results indicate that NGC 4569 is a LINER II galaxy, which is consistent with previous classifications based on optical spectroscopy.

Acknowledgments

We wish to thank...
A sizeable minority of galactic nuclei has emission-line ratios which are intermediate between those of “pure” LINERs and those of typical H II regions powered by hot stars; these galaxies would be classified as LINERs except that their [O II] λ5007/λ4363/λ4959 line strengths are too small in comparison with other lines to meet the formal LINER criteria. Objects falling into this category have been dubbed “transition” galaxies by Ho et al. (1993), and although this nomenclature is somewhat ambiguous we adopt it here for consistency with the spectroscopic survey of Ho et al. (1997a). That survey defined the transition class in terms of the following flux ratios:

\[
\begin{align*}
[\text{O III}] \lambda 5007/\text{H} \beta & < 3, \\
0.08 & \leq [\text{O III}] \lambda 6300/\text{H} \alpha < 0.17, \\
[N \text{ II}] \lambda 6583/\text{H} \alpha & > 0.6, \\
[S \text{ II}] \lambda 6716, 6731/\text{H} \alpha & > 0.4.
\end{align*}
\]

Filippenko & Terlevich (1992) have used the term “weak-[O II] LINERs” to refer to galaxies having [N II] λ6583/λ6300 > 0.6 (typical of LINERs) but which have [O II] λ6300/λHα < 1/6. This category is essentially identical to the transition class of Ho et al. (1993, 1997a), and we will refer to these galaxies as transition objects in this paper.

According to the survey results of Ho et al. (1997b), this transition class accounts for 13% of all nearby galaxies, making them about as numerous as Seyfert nuclei. The Hubble type distribution of transition galaxies is intermediate between that of LINERs, which are most common in E/S0/SA galaxies, and that of H II nuclei, which occur most often in Hubble types later than Sb (Ho et al. 1997b). Roughly 20% of galaxies with Hubble types ranging from S0 to Sbc belong to the transition class. There is not a consensus, however, as to whether these transition objects should be regarded as star-forming nuclei, as accretion-powered active nuclei, or as composite objects powered by an AGN and by hot stars in roughly equal proportion.

There is a large body of literature on the subject of the excitation mechanism of LINERs which is relevant to the similar transition class. A variety of physical mechanisms has been proposed to explain the emission spectra of LINERs, including shocks, photoionization by a nonstellar ultraviolet (UV) and X-ray continuum, and photoionization by hot stars. (See Filippenko 1996 for a review.)

The possibility that LINERs (and Seyfert nuclei as well) might be photoionized by starlight was raised by Terlevich & Melnick (1985), who suggested that very hot (Teff ≈ 10^5 K) Wolf-Rayet (W-R) stars in a metal-rich starburst could give rise to an ionizing continuum with a nearly power-law shape in the extreme-UV. More recent atmosphere models have indicated substantially lower temperatures for W-R stars, however, casting doubt on the Warner hypothesis (Leitherer et al. 1992). Subsequent photoionization models have attempted to explain LINER and transition-type spectra as resulting from massive main-sequence stars. Filippenko & Terlevich (1992) found that the spectra of weak-[O II] LINERs could be explained in terms of photoionization by O3-O4 stars having effective temperatures of ≥ 45,000 K, at ionization parameters of U ≈ 10^{-3.7} to 10^{-2.3}. Shields (1992) carried this line of argument farther, proposing that genuine LINER spectra could be generated by early O stars with Teff ≈ 50,000 K, provided that a high-density component (n_e ≈ 10^5 cm^{-3}) is present in the NLR; the high densities are needed to boost the strengths of high critical-density emission lines, most notably [O II] λ6300. Similar conclusions were reached by Schulz & Fritsche (1994), who explored the effects of absorption by ionized gas as a means to harden the effective ionizing spectrum. Recent observations, particularly in the UV and X-ray bands, have provided convincing evidence that many LINERs are in fact AGNs, particularly the “Type 1” LINERs which have a broad component to the Hα emission line (for a recent review see Ho 1999). The possibility has remained, however, that some LINERs and transition nuclei are powered entirely by bursts of star formation.

An important shortcoming of the model calculations performed by Filippenko & Terlevich (1992) and Shields (1992) is that the ionizing continuum used as input were those of single O-type stars; these studies did not address the question of whether a LINER or transition-type spectrum could result from the the integrated ionizing continuum of a young stellar cluster. Compared with these single-star models, the contribution of late-O and B stars will soften the ionizing spectrum, making the emission-line ratios tend toward those of normal H II regions. W-R stars, on the other hand, will harden the ionizing spectrum during
the period when these stars are present, roughly \(3 - 6\) Myr after the burst. Another drawback of the O-star models is that they require the presence of stars with effective temperatures higher than are thought to occur in H II regions of solar or above-solar metallicity, in order to produce a LINER or transition-type spectrum rather than an H II region spectrum. Their applicability to galactic nuclei is therefore somewhat unclear.

Other mechanisms have been proposed for generating LINER or transition-type spectra. Shock excitation by supernova remnants in an aging starburst may give rise to some transition objects; the nucleus of NGC 253 is a likely candidate for such an object (Engelbracht et al. 1998). Also, post-AGB stars and planetary nebula nuclei will produce a diffuse ionizing radiation field which could be responsible for the very faint LINER emission (with Hα equivalent widths of \(-1\) Å) observed in some ellipticals and spiral bulges (Binette et al. 1994).

An alternate possibility is that the transition galaxies may simply be composite systems consisting of an active nucleus surrounded by star-forming regions. For a galaxy at a distance of 10 Mpc, for example, a 0.5-wide spectroscopic aperture will include H II regions within 50 pc of the nucleus. Galaxies having emission lines both from a LINER nucleus and from surrounding star-forming regions, in roughly equal proportions, will appear to have a transition-type spectrum. This interpretation was advocated by Ho et al. (1993) as the most likely explanation for the majority of transition galaxies, and is consistent with the observed Hubble type distribution for the transition class. Other authors have similarly contended that transition galaxies are AGN/H II region composites, based on optical line-profile decompositions (Véron et al. 1997; Gonçalves et al. 1999) and near-infrared spectra (Hill et al. 1999). Two of the 65 transition nuclei observed in the Ho et al. (1997b) survey have a broad component to the Hα emission line, indicating the likely presence of an AGN, and it is probable that many more transition nuclei contain obscured AGNs which were not detected in the optical spectra. On the other hand, radio observations do not appear to support the composite AGN/starburst interpretation. In a VLA survey of nearby galactic nuclei, Nagar et al. (1999) find compact, flat-spectrum radio cores in more than 50% of LINER nuclei, but in only 6% (1 of 18) of transition objects. This discrepancy suggests that the simple picture of an ordinary LINER surrounded by star-forming regions may not apply to the majority of transition objects.

Recent results from the Hubble Space Telescope (HST) have shed new light on the question of the excitation mechanism of transition nuclei. As shown by Mace et al. (1998), the UV spectrum of the well-known transition nucleus in NGC 4569 over 1200-1600 Å is virtually identical to that of a W-R knot in the starburst galaxy NGC 1741, indicating that O stars with ages of a few Myr dominate the UV continuum. Mace et al. (1998) find that the nuclear star cluster in NGC 4569 is producing sufficient UV photons to ionize the surrounding narrow-line region, a key conclusion which provides fresh motivation to study stellar photoionization models. The brightness of the NGC 4569 nucleus, and the consequently high S/N observations that have been obtained, make it one of the best objects with which to study the transition phenomenon.

The recent availability of the STARBURST99 model set (Leitherer et al. 1999) has prompted us to reexamine the issue of ionization by hot stars in LINERs and transition nuclei. These models give predictions for the spectrum and luminosity of a young star cluster, for a range of values of cluster age, metal abundance, and stellar initial mass function (IMF) properties. Using the photoionization code CLOUDY (Ferland et al. 1998) in combination with the STARBURST99 model continuum, we have calculated the expected emission-line spectrum of an H II region illuminated by a young star cluster, to test the hypothesis that some LINERs and transition nuclei may be powered by starlight. Similar calculations have been performed by Stasińska & Leitherer (1996), but for the physically distinct case of metal-poor objects representing H II galaxies. Other examples of photoionization calculations for H II regions using evolving starburst continua are presented by García-Vargas & Díaz (1994), García-Vargas et al. (1995), and Bresolin et al. (1999).

2. The Nucleus of NGC 4569

Before describing the photoionization modeling, we review the properties of NGC 4569, as it is
among the best-known examples of the transition class. NGC 4569 is a Virgo cluster spiral of type Sab, with a heliocentric velocity of $-235 \text{ km s}^{-1}$, and we assume a distance of $16.8 \text{ Mpc}$ for consistency with the catalog of Ho et al. (1997a). Its nucleus is remarkably bright for a non-Seyfert, and so compact in the optical that Humason (1936) suspected it to be a foreground Galactic star. It is also an unusually bright UV source, with the highest 2200 Å luminosity of the LINERs and transition objects observed by Maoz et al. (1995) and Barth et al. (1998). HST Faint Object Spectrograph (FOS) spectra show that the UV continuum is dominated by massive stars, with prominent P Cygni profiles of C IV $\lambda 1549$, Si IV $\lambda 1400$, and N V $\lambda 1240$ (Maoz et al. 1998). The UV spectrum is nearly an exact match to the spectrum of one of the starburst knots in the W-R galaxy NGC 1741, an object with a likely age in the range 3–8 Myr (Conti et al. 1996). The optical spectrum of the NGC 4569 nucleus is dominated by the light of A-type supergiants, providing additional evidence for recent star formation (Keel 1996).

One key result of the Maoz et al. (1998) study was the conclusion that the nuclear starburst in NGC 4569 is producing sufficient numbers of ionizing photons to power the narrow-line region, assuming that the surrounding nebula is ionization-bounded, even without correcting for the effects of internal extinction on the UV continuum flux. In fact, there appears to be substantial extinction within NGC 4569, as demonstrated by the UV continuum slope as well as the presence of deep interstellar absorption features (Maoz et al. 1998). Ho et al. (1997a) derive an internal reddening of $E(B-V) = 0.46$ mag from the H$\alpha$/H$\beta$ ratio, while Maoz et al. (1998) estimate a UV extinction of $A \approx 4.8$ mag at 1300 Å by comparison of the observed UV slope with the expected spectral shape of an unreddened starburst.

Despite the fact that NGC 4569 is often referred to as a LINER, and in some cases presumed to contain an AGN on the basis of that classification, there is no single piece of evidence which conclusively demonstrates that an AGN is in fact present at all. The HST images and spectra are all consistent with the nucleus being a young, luminous, and compact starburst region. No broad-line component is detected on the H$\alpha$ emission line (Ho et al. 1997a), and no narrow or broad emission lines are visible at all in the UV spectrum other than the P Cygni features that are generated in O-star winds (Maoz et al. 1998). Only the optical emission-line ratios point to a possible AGN classification. In a thorough study of optical and $I$/$R$/$E$ UV spectra, Keel (1996) concluded that there was no evidence for the presence of an AGN in NGC 4569, and that any AGN continuum component, if present, must have an unusually steep spectrum.

Furthermore, while the nucleus of NGC 4569 is certainly extremely compact, the UV and optical HST images show that the nucleus is not dominated by a central point source. At 2200 Å, the nucleus appears extended in WFPC2 images with FWHM sizes of 13 and 9 pc along its major and minor axes (Barth et al. 1998). Optical WFPC2 images have been discussed recently by Pogge et al. (1999), who state that the nucleus is unresolved by HST. We have obtained these same images from the HST archive. While the nucleus is certainly compact, we find that it is clearly extended even at the smallest radii. A 12-second, CR-SPLIT exposure in the F547M (V-band) filter is unsaturated and allows a radial profile measurement. We find a FWHM size of 14 pc by 8 pc along the major and minor axes, consistent with the size of the nuclear cluster measured at 2200 Å, Barth et al. (1998) estimated that at most 23% of the nuclear UV flux could come from a central point source. From the equivalent widths of stellar-wind features in the UV spectrum, Maoz et al. (1998) give a similar upper limit of $\sim 20\%$ to the possible contribution of a truly featureless continuum to the observed UV flux.

X-ray observations of NGC 4569 with ROSAT have revealed a source coincident with the nucleus which is unresolved at the $2''$ resolution of the HRI camera (Colbert & Mushotzky 1999). This does not necessarily indicate that an AGN is present, however, as the optical/UV size of the starburst core is an order of magnitude smaller than the HRI resolution. ASCA observations show that the X-ray emission is extended over arcminute scales in both the hard (2–7 keV) and soft (0.5–2 keV) bands (Terashima et al. 1999). Interestingly, the compact source seen in the ROSAT image is detected only in the soft ASCA band, while there is no detectable contribution from a compact, hard X-ray source. The spectral shape of the compact
soft X-ray component is consistent with an origin either in an AGN or in X-ray binaries (Tschöke & Hensler 1999), but the lack of a compact hard X-ray source argues against the AGN interpretation. If an AGN is present, it must be highly obscured even at hard X-ray energies, with an obscuring column of \( N_H > 10^{23} \) cm\(^{-2}\) (Terashima et al. 1999). In radio emission, VLA observations show that the NGC 4569 nucleus is an extended source with a size of 4\(^\prime\) and no apparent core (Neff & Hutchings 1992), in contrast with the compact, AGN-like cores found in some LINERs (Falcke et al. 1998).

Shock excitation has often been considered as a mechanism to power the narrow emission lines in LINERs. However, the lack of narrow emission features in the UV spectrum of NGC 4569 argues against shock-heating models for this object, as existing shock models generally predict strong UV line emission (e.g., Dopita & Sutherland 1996). Shock-excited filaments in supernova remnants show strong emission in high-excitation UV lines such as C IV \( \lambda 1549 \) and He II \( \lambda 1640 \) (e.g., Blair et al. 1991, 1995) which are altogether absent from the NGC 4569 spectrum. Similarly, the shock-excited nuclear disk of M87 (Dopita et al. 1997) has a high-excitation UV line spectrum which bears no resemblance to the NGC 4569 spectrum. From an analysis of infrared spectra, Alonso-Herrero et al. (1999) proposed that the NGC 4569 nucleus is powered by an 8–11 Myr-old starburst, by a combination of stellar photoionization and shock heating from supernova remnants. While this hypothesis may be applicable to some LINERs and transition galaxies, the UV spectrum of NGC 4569 shown by Maoz et al. (1998) is inconsistent with a burst of such advanced age, as the P Cygni features of C IV, Si IV, and N V would have disappeared from a single-burst population after about 6 Myr.

The overall picture emerging from these observations is that the NGC 4569 nucleus is a compact, luminous, and young starburst. The only reason to invoke the presence of an AGN at all would be to explain the higher strengths of the low-ionization forbidden lines in comparison with values observed in normal H II nuclei. If it were indeed possible for a young starburst to produce transition or LINER-type emission lines in the surrounding gas, then there would be no reason to consider AGN models for NGC 4569.

3. Photoionization Calculations

3.1. The Ionizing Continuum

As discussed by Filippenko & Terlevich (1992) and Shields (1992), the key ingredient necessary for generating a LINER or transition-type emission-line spectrum is an ionizing continuum which is harder than that produced by typical clusters of OB stars. A harder continuum will produce a more extended partially-ionized zone in the surrounding H II region, boosting the strength of the low-ionization lines which are typical of LINER spectra: [O II] \( \lambda 3727 \), [N II] \( \lambda\lambda 6548,6583 \), and [S II] \( \lambda\lambda 6716,6731 \).

To represent the ionizing continuum of a young starburst, we have chosen the STARBURST99 model set; we refer the reader to Leitherer et al. (1999) for the details of the methods used to construct these models. Briefly, the STARBURST99 code employs the Geneva stellar evolution models of Meynet et al. (1994), with enhanced mass-loss rates, for high-mass stars. Atmospheres are represented by the models compiled by Lejeune et al. (1997) and Schmutz et al. (1992). Figures 1–12 of Leitherer et al. (1999) display the spectral energy distributions of the STARBURST99 model clusters for a range of burst ages and for a variety of initial conditions. From the figures, some important trends are readily apparent. During the first 2 Myr after an instantaneous burst, the continuum is dominated by the hottest O stars, and there is essentially no emission below 228 \( \AA \), corresponding to the ionization energy of He\(^+\). The appearance of W-R stars during the period 3–5 Myr after the burst results in a dramatic change in the UV continuum, as these stars emit strongly in the He\(^{++}\) continuum below 228 \( \AA \). From 6 Myr onwards, the W-R stars disappear and the UV continuum rapidly fades and softens as the burst ages. Only the models with an upper mass limit of \( M_{up} = 100 M_\odot \) generate the hard, W-R-dominated UV continuum; the model sequences with \( M_{up} = 30 M_\odot \) do not generate significant numbers of photons below 228 \( \AA \) for any ages because the progenitors of W-R stars are not present in the initial burst. Constant star-formation rate models with \( M_{up} = 100 M_\odot \) form W-R stars continuously after 3 Myr, but the overall shape of the UV continuum
is softer than in the instantaneous burst models, because of the continuous formation of luminous O stars.

These results provide a useful starting point for the photoionization calculations. If it is possible for the H II region surrounding a young cluster to resemble a LINER or transition object, then this is most likely to occur when the ionizing continuum is hardest, when W-R stars are present during $t \approx 3 - 5$ Myr after a burst. Very massive stars (in the range $30-100 \, M_\odot$ or greater) must be present in the burst or else the requisite W-R stars will not appear. The formation of W-R stars is enhanced at high metallicity, so the ability to generate a LINER or transition-type spectrum may be a strong function of metal abundance as well as age.

3.2. Model Grid

To create grids of photoionization models, we fed the UV continua generated by the STARBURST99 models into the photoionization code CLOUDY (version 90.04; Ferland et al. 1998). For each time step, a grid of models was calculated by varying the nebular density and the ionization parameter, which is defined as the ratio of ionizing photon density to the gas density at the ionized face of a cloud. Real LINERS and transition nuclei are likely to contain clouds with a range of values of density and ionization parameter, and more general models incorporating density and ionization stratification can be constructed as linear combinations of these simple single-zone models.

All models were run with the following range of parameters: burst age from 1 to 10 Myr at increments of 1 Myr, with log $U$ ranging from $-2$ to $-4$ at increments of 0.5, and a constant density ranging from log (n$_H$/cm$^{-3}$) = 2 to 6 at increments of 1. As a starting point, we computed a grid for an instantaneous burst with an IMF having a power-law slope of $-2.35$, $M_{\text{top}} = 100 \, M_\odot$, solar metallicity in stars and gas, and a single plane-parallel slab of gas with no dust; we will refer to this as model grid A. The solar abundance set was taken from Grevesse & Anders (1989) and Grevesse & Noels (1993). Other grids were computed as variations on this basic parameter set, with the following modifications made in different model runs: a constant star-formation rate; metallicity 0.2, 0.4, or 2$Z_\odot$ in both stars and gas; and spherical geometry for the nebula. To assess the effects of the highest-mass stars, we also ran custom model grids, via the STARBURST99 website, with $M_{\text{top}} = 70$ and 120 $M_\odot$.

The depletion of heavy elements onto grains can result in marked changes to the emergent emission-line spectrum of an H II region, both by removing gas-phase coolants from the nebula and by grain absorption of ionizing photons, which will modify the effective shape of the ionizing continuum. In metal-rich H II regions, these effects will tend to boost the strengths of the low-ionization emission lines relative to the dust-free case (Shields & Kennicutt 1995). To assess the effects of dust in transition nuclei, we calculated additional model grids which included dust grains with a Galactic ISM dust-to-gas ratio along with the corresponding gas-phase depletions. The dusty models were all calculated using the solar abundance set for the undepleted gas. Dust grains were assumed to have the optical properties of Galactic ISM grains, as described by Mathis, Rumpl, & Nordsieck (1977), Draine & Lee (1984), and Martin & Rouleau (1991). From the CLOUDY output files, we tabulated the strengths relative to H$\beta$ of the major emission lines which are prominent in LINERs.

The calculations were performed under the assumption that the H II region is ionization bounded. For this case, the outer extension of the cloud was set to be the radius at which $T_e$ falls to 4000 K, beyond which essentially no emission is generated in the optical or UV lines. As a test, we ran a grid of models with the stopping temperature set to 1000 K, and we verified that the emission-line ratios were essentially identical to the default case of 4000 K stopping temperature. We also verified that the important diagnostic line ratios differed by $< 0.1$ dex between the spherical and plane-parallel cases when all other input parameters were unmodified, and all results discussed in this paper refer to the plane-parallel models. In the calculations, the longest timescales for atomic species to reach equilibrium were of order $10^3$ years, much shorter than the evolution timescale of the stellar cluster, justifying the assumption that each time step of the cluster evolution could be used independently to calculate the nebular conditions. Table 1 gives a
summary of the model parameters, for the model grids which appear in the following discussion.

4. Discussion

4.1. Model Results

The model results are displayed in Figures 1–9. To compare the model outputs with the observed properties of a variety of galaxy types, we have used the emission-line data compiled by Ho et al. (1997a). This catalog has the advantages of a homogeneous classification system, small measurement aperture (2′′ × 4′′), and careful starlight subtraction to ensure accurate emission-line data. In order to reduce confusion and to keep the sample of comparison objects to a reasonable number, we included only objects with unambiguous classifications as H II, LINER, transition, or Seyfert. Objects with borderline or ambiguous classifications, such as “LINER/Seyfert,” were excluded for clarity. The comparison sample was further reduced by excluding galaxies in which any of the emission lines Hα, Hβ, [O III] λ5007, [O I] λ6300, [N II] λ6583, or [S II] λ6716,6731 was undetected or was flagged as having a large uncertainty in flux (“b” or “c” quality flags). The measured line ratios are corrected for both Galactic and internal reddening.

Figure 1 plots the ratio [O III] λ5007/Hβ against [O I] λ6300/Hα at a burst age of 4 Myr, for the solar-metallicity model grids A, B, C, and D. The model results are plotted for a density of n_H = 10^3 cm^{-3}, as an approximate match to the density of n_e = 500 cm^{-3} measured for NGC 4569 (Ho et al. 1997a). The diagram shows that the instantaneous burst models (A and B) are a good match to the line ratios of the transition nuclei, for log U ≈ −3.5. The dusty models from grid B fall more centrally within the region defined to contain transition objects, but the models without dust still closely match transition nuclei having lower [O I] λ6300/Hα ratios. Figures 2 and 3 show the corresponding diagrams for [N II] λ6583/Hα and for [S II] λ6716,6731/Hα, respectively. In both cases we find that the single-burst models span the region occupied by transition nuclei in the diagnostic diagrams.

In the constant star-formation rate models (C and D), the UV continuum remains softer than in the W-R-dominated phase of the instantaneous burst models, because of the ongoing formation of luminous O stars. As a result, the low-ionization emission lines are significantly weaker than in the instantaneous burst models at 4 Myr. These constant star-formation rate sequences are a reasonable match to the region of H II nuclei in the diagram, and for [N II]/Hα and [S II]/Hα the agreement with H II nuclei is improved at lower densities of n_e = 10^2 cm^{-3}, a value more typical of H II nuclei. These constant star-formation rate models are probably appropriate for galaxies having spatially extended, ongoing star formation in their nuclei.

We note that the model curves shown in the figures should not be expected to follow the locus of H II nuclei in each plot, despite the fact that the models are generated with a starburst continuum. The range of line ratios observed in H II regions is primarily a sequence in metal abundance (McCall, Rybksi, & Shields 1985), while our models are shown as sequences in U for a given metallicity and density. Another point to note about the diagrams is that some of the transition galaxies fall outside the region nominally defined for transition objects, particularly in the [O I]/Hα ratio (Figure 1). These galaxies were classified as transition objects by Ho et al. (1997a) on the basis of meeting the majority of the classification criteria. Similarly, some overlap can be seen in the diagrams between the regions occupied by LINERs and Seyfert nuclei; this again reflects the fact that galaxies span a continuous range in the values of these emission-line ratios.

The variation of [O I] line strength as a function of density is shown in Figure 4 for model grid A at t = 4 Myr. For the range of densities considered (n_H = 10^2 to 10^6 cm^{-3}), the models closely overlap the transition region in the diagram at log U ≈ −3.5. Introducing ISM depletion and dust grains to the nebula primarily increases the [O I]/Hα ratio at low density. As expected, the [O I]/Hα ratio increases with n_H up to densities of 10^5 cm^{-3}, while at densities approaching the critical density of the λ6300 transition (1.6 × 10^6 cm^{-3}) this ratio saturates and begins to turn over.

Figure 5 shows the [O I]/Hα ratio as a function of burst age (at n_e = 10^5 cm^{-3}) for model grid A, for ages of 2 to 6 Myr. This diagram highlights the dramatic changes that W-R stars generate in the surrounding nebula. From 3 to 5 Myr after
the burst, when W-R stars dominate the UV continuum, the harder ionizing continuum boosts the strength of [O III] by an order of magnitude and the model sequences appear adjacent to the transition region, with relatively little evolution in the line ratios during this period. As the burst ages beyond 6 Myr, the [O III]/Hα ratio continues to fall, and the emission-line strengths drop rapidly as the ionizing continuum softens and its luminosity decreases. At \( Z = 2Z_\odot \), the WR-dominated phase occurs slightly later, during time steps 4, 5, and 6 Myr. The [N II]/Hα and [S II]/Hα ratios have a similar dependence on burst age, and are displayed in Figures 6 and 7, respectively; these results are quite similar to the calculations presented by Leitherer et al. (1992) to illustrate the effects of the W-R continuum on the [N II]/Hα ratio. While the [O III]/Hα ratios in the models at \( \log U \leq -3.5 \) are too low by \( \sim 0.1 - 0.2 \) dex to fit within the nominal transition region, they still closely match the transition nuclei having relatively low values for [O III]/Hα, and the low-ionization line strengths can be further enhanced by the inclusion of dust and depletion (as in Figure 1).

One puzzling aspect of Figure 5 is that for ages outside the range 3–5 Myr, the models predict [O III]/Hα ratios too low to match the majority of H II nuclei. Stasińska & Leitherer (1996) and Martin (1997) discuss the same problem in the context of low-metallicity starburst galaxies. They propose that shocks generated by supernovae and stellar winds provide the additional [O III] emission, without making a significant contribution to the [O III] or [O III] line strengths. Shocks could play a similar role in transition galaxies, as in the model of Alonso-Herrero et al. (1999), although the lack of high-excitation UV line emission in transition nuclei is problematic for the shock hypothesis. A higher upper mass cutoff alleviates this problem to some extent, at least for very young bursts. Increasing \( M_{\text{up}} \) to 120 \( M_\odot \) boosts [O III]/Hα by \( \sim 0.2 \) dex for ages of \( \lesssim 3 \) Myr. Due to the very short lifetimes of the highest-mass stars, however, the \( M_{\text{up}} \) = 120, 100, and 70 \( M_\odot \) model grids result in identical emission-line spectra from \( \sim 4 \) Myr onward.

Metal abundance is an additional parameter which must be considered. The models displayed up to this point were all calculated for a solar abundance set, while the nuclei of early-type spirals are likely to have enhanced heavy-element abundances. As discussed by Leitherer et al. (1999), the continuum shortwards of 228 Å is strongest in the high-metallicity models, because the increased mass-loss rates lead preferentially to the formation of W-R stars at high metal abundance. Figure 8 plots the [O III]/Hα ratio for abundances of \( Z = 0.2, 0.4, 1, \) and \( 2 Z_\odot \), at a density of \( n_H = 10^3 \text{ cm}^{-3} \) and \( t = 4 \) Myr. From this diagram, it is clear that solar or higher abundances are necessary to match the [O III] strengths of the transition nuclei; at lower abundances the line ratios are a better match to those of the high-excitation (low-metallicity) H II nuclei. Figure 9 displays the density dependence of the [O III]/Hα ratio for the \( Z = 2Z_\odot \) model grid; by comparison with the solar-metallicity model grid in Figure 4, the higher abundances result in a lower-excitation spectrum with enhanced [O III] emission, due to the harder extreme-UV continuum.

It would be advantageous to compare the model results with a wider variety of emission lines. Unfortunately, measurements of other optical emission lines are scarce for transition nuclei. The Ho et al. survey did not include the [O III] \( \lambda 3727 \) line, and there is no other homogeneous catalog of [O III] measurements for transition galaxies. To be consistent with a LINER or transition-type classification, a model calculation must result in the flux ratio \([\text{O III} \lambda 3727 / [\text{O III} \lambda 5007] > 1.\) In fact, all of the models with \( \log U \leq -3 \) do satisfy this criterion. Thus, any of our models which is consistent with the Ho et al. LINER or transition classification criteria is also consistent with the original Heckman (1980) criterion for the [O III]/[O III] ratio in LINERs. The relative strengths of UV lines such as C II \( \lambda 2326, \) C III \( \lambda 1909, \) and C IV \( \lambda 1549 \) can provide further diagnostics, but none of these lines is detected in NGC 4569 (Macoz et al. 1998). The only other transition nucleus having HST UV spectra available is NGC 5055, and its spectrum appears to be devoid of UV emission lines as well (Macoz et al. 1998).

We ran one additional model grid to test whether different model atmospheres for O stars would lead to different results. The STARBURST99 continua were calculated using stellar atmosphere models compiled by Lejeune et al. (1997), which are based on the Kurucz (1992) model set for the massive stellar component. The
recent CoStar model grid of Schauer & de Koter (1997), which includes non-LTE effects, stellar winds, and line blanketing for O stars, makes dramatically different predictions for the ionizing spectra. As shown by Schauer & Vacca (1998), the CoStar models yield a luminosity in the He$^+$ continuum which is four orders of magnitude greater than that predicted by the Kurucz models, for the most massive O stars which dominate the UV luminosity at burst ages of < 3 Myr. In the CoStar-based models the photon output of the cluster below 228 Å is essentially constant from 0 to 5 Myr. To investigate the effects of this harder O-star continuum on the emission-line spectra, we ran a grid of models using the evolving starburst continua computed by Schauer & Vacca (1998) with the CoStar atmospheres. Model parameters were the same as for model grid A except that an upper mass limit of 120 $M_\odot$ was used. We find that using the CoStar atmospheres has a relatively minor effect on our results. In comparison with the STARBURST99-based models having $M_{\text{mp}} = 120 M_\odot$, the CoStar model grid yields an increase in the [O III]/H$\alpha$ ratio of $\sim 0.1 - 0.15$ dex for $t < 6$ Myr, while [N II]/H$\alpha$ and [S II]/H$\alpha$ are essentially unaffected. During the period $t < 3$ Myr, the CoStar-based models result in an H II region spectrum, demonstrating that W-R stars are still required in order to generate LINER or transition-type line ratios.

The strength of the [Ca II] emission lines at 7291 and 7324 Å is often used as a diagnostic of dust and depletion, because in the absence of depletion these lines are predicted to be strong in photoionized gas (e.g., Kingdon et al. 1995; Villar-Martín & Binette 1996). (The $\lambda$7291 line is a clearer diagnostic since $\lambda$7324 is blended with [O II] $\lambda$7325.) However, for a 4 Myr-old burst with nebular conditions of $n_e = 10^3$ cm$^{-3}$, log $U = -3.5$, and an undepleted solar abundance set, our calculations yield a maximum prediction of only 0.2 for the ratio of [Ca II] $\lambda$7291, 7324 to H$\beta$. Only at very low ionization parameters ($\lesssim 10^{-4.5}$) does the [Ca II] emission become stronger than H$\beta$. Since H$\beta$ is only barely visible in the spectra of many transition objects (prior to careful starlight subtraction, at least), typical observations may not have sufficient sensitivity to detect faint [Ca II] lines in these objects. High-quality spectra of LINERs do not show [Ca II] emission (Ho et al. 1993), indicating that Ca is likely to be depleted onto grains in these objects, but similar data are not generally available for transition nuclei. If the [Ca II] lines are found to indicate a high level of depletion onto dust grains in transition nuclei, this would also provide a further argument against shock-heating models, as shocks will tend to destroy grains (e.g., Morse et al. 1996).

4.2. The Nature of Transition Nuclei

The results shown in the preceding figures demonstrate that the starburst models are in fact able to reproduce the major diagnostic emission-line ratios of transition nuclei with reasonable accuracy, during the period $t = 3$–5 Myr when W-R stars are present. For a density of $10^3$ cm$^{-3}$ and an age of 4 Myr, the solar-metallicity models with and without depletion bracket the range of values observed in real transition nuclei for the line ratios [O I]/H$\alpha$, [N II]/H$\alpha$, and [S II]/H$\alpha$. We do not attempt to fine-tune a model to produce an exact match with the spectrum of NGC 4569, but the basic solar-metallicity dust-free model at $t = 4$ Myr with $n_e = 10^3$ cm$^{-3}$ and log $U = -3.5$ closely fits the observed [O I]/H$\alpha$ ratio, while overpredicting [S II]/H$\alpha$ by $\sim 0.2$ dex and underpredicting [N II]/H$\alpha$ by $\sim 0.1$ dex.

We emphasize that the starburst models are only able to produce transition-type spectra for the case of an instantaneous burst; that is, when the burst duration is shorter than the timescale for evolution of the most massive stars. Multiple-burst populations can only yield a transition spectrum if the dominant population is $\sim 3$ – 5 Myr old and the older or younger bursts do not contribute significantly to the ionizing photon budget. Models with a constant star-formation rate produce H II region spectra at all ages, as the softer ionizing continua do not produce sufficient [O I] 6300 emission in the surrounding H II region to match transition-type spectra. The parameter which is most important for determining the hardness of the ionizing continuum is the number ratio of W-R stars to O stars, which exceeds $\sim 0.15$ during the W-R-dominated phase in the STARBURST99 models at solar metallicity, and approaches or exceeds unity at $Z = 2 Z_\odot$. In the constant star-formation rate models at solar metallicity, the W-R/O ratio levels off at $\sim 0.06$ after about 4 Myr. The compact size of the NGC 4569
nucleus is consistent with the requirement that the burst duration must be brief (\( \lesssim 1 \) Myr) in order to generate a transition-type spectrum. The FWHM size of the starburst core in NGC 4569 is only \( \sim 10 \) pc. For such a burst to occur in \( \lesssim 1 \) Myr would require a propagation speed for star formation of only \( \sim 10 \) km s\(^{-1}\). In fact, the typical velocities in the NGC 4569 nuclei are much greater than 10 km s\(^{-1}\); the [N II] \( \lambda 6583 \) line has a velocity width of 340 km s\(^{-1}\) (Ho et al. 1997a). Thus, the NGC 4569 nuclei could represent the result of a single, rapid burst of star formation.

Although our results suggest that transition galaxy spectra may be attributed to a starburst with a high W-R/O-star ratio, the demographics of transition nuclei and H II nuclei indicate that many transition galaxies are probably not formed by this mechanism. In the STARBURST99 models, the W-R-dominated phase in an instantaneous burst lasts for \( \sim 3 \) Myr (i.e., 3 time steps in the calculations). An H II region surrounding an instantaneous burst will be visible for \( \sim 6 \) Myr, after which the emission lines will fade rapidly (e.g., García-Vargas & Díaz 1994). Thus, for an instantaneous burst population, the transition phase and the H II nucleus phase will have approximately equal lifetimes. If all H II nuclei consisted of instantaneous burst stellar populations with nebular conditions conducive to the formation of transition-type spectra, then H II nuclei and transition nuclei should be roughly equal in number. In reality, it is likely that a large fraction of star-forming nuclei contain multiple bursts of star formation and/or conditions of low density or low metallicity, so all star-forming nuclei should not be expected to evolve through a transition-type phase. Although it is difficult to make specific predictions, it is probably safe to conclude that for a given Hubble type, transition nuclei generated solely by starbursts should be considerably less numerous than ordinary H II nuclei.

The statistics compiled by Ho et al. (1997b) provide a basis for comparison. In early-type galaxies (E and S0), transition nuclei outnumber H II nuclei by a 3-to-1 margin. Only for Hubble types Sb and later do H II nuclei begin to outnumber transition nuclei by a factor of 2 or more. The most straightforward interpretation of this trend is that in early-type host galaxies, the majority of transition nuclei are actually AGN/H II region composites, as proposed by Ho et al. (1993) and others. At intermediate and late Hubble types, the population of transition nuclei may consist of both composite objects and “pure” starbursts evolving through the W-R-dominated phase.

The presence of transition nuclei in a small fraction (\( \sim 10\% \)) of elliptical galaxies (Ho et al. 1997b) presents a particularly intriguing problem. The Ho et al. survey detected five transition nuclei in ellipticals but not a single case of an elliptical galaxy hosting an H II nucleus. Given that the models which have been considered for transition nuclei involve star formation, either alone or in combination with an AGN, this observation is rather puzzling. Perhaps faint AGNs in elliptical nuclei can produce transition-type spectra without substantial star formation activity. Four of the five transition nuclei found in ellipticals by Ho et al. (1997a) have borderline or ambiguous spectroscopic classifications, however, so “pure” transition nuclei in ellipticals are evidently quite rare.

Given these results, one might expect to see transition-type emission spectra in some fraction of disk H II regions in spiral galaxies, but in fact such spectra are never found. Single-burst models for disk H II region spectra are only compatible with observed line ratios for model ages of \( t < 3 \) Myr (Bresolin et al. 1999), as the harder ionizing spectrum after 3 Myr makes the models overpredict the strengths of the low-ionization lines. Bresolin et al. suggest that either current stellar evolution models are at fault, or that disk H II regions are disrupted before reaching an age of 3 Myr, in which case the W-R phase would not be observed in the nebular gas. An alternate (and perhaps more attractive) possibility is that the majority of H II nuclei, as well as disk H II regions, are better described by the models with constant star-formation rate, or contain multiple bursts of star formation with an age spread of a few Myr, which would result in a spectrum similar to the constant star-formation rate models.

For understanding the physical nature of transition objects, the observational challenge is to search for any unambiguous signs of nonstellar activity. Detection of broad Hα emission, or a compact source of hard X-ray emission with a power-law spectrum, would provide evidence for an AGN component. High-resolution optical spectra (from HST) could provide a means to spatially resolve
a central AGN-dominated narrow-line region from the surrounding starburst-dominated component. Since direct evidence for accretion-powered nuclear activity in transition nuclei is generally lacking, it should not be assumed that any given transition object actually contains an AGN unless observations specifically support that interpretation.

One further effect that should be considered in starburst models in the future is photoionization by the X-rays generated by the starburst. X-ray binaries and supernova remnants will provide high-energy ionizing photons, resulting in a spatially extended source of soft X-ray emission as observed in the nucleus of NGC 3555 (Terrasima et al. 1999), for example. (The massive main sequence stars will contribute only a negligible amount to the total X-ray luminosity of a starburst; see Helfand & Moran 1999.) Photoionization by X-rays will naturally lead to an enhancement of the low-ionization forbidden lines, and this could contribute to the excitation of some transition galaxies.

4.3. LINERs

The strength of [O III] λ5000 is the key distinguishing factor between LINERs and transition nuclei, and matching the observed strength of this line is the major challenge of starburst models for LINERs. Our calculations show that LINER spectra can only be generated by the STARBURST99 clusters under a very specific and limited range of circumstances. Model grids A and B, while matching the [O III] / Hα ratio of transition nuclei quite well, do not overlap at all with the main cluster of LINERs in Figure 1, even at high densities and even when depletion and dust grains are included. Only grid G with Z = 2Z⊙ is able to replicate the high [O III] / Hα ratios of most LINERs, and only during t ≈ 4–6 Myr and at densities of nH ⩾ 10^5 cm⁻³. In agreement with previous models, we find that values of log U ≈ −3.5 to −3.8 reproduce the observed [O III] / Hα ratios of LINERs. However, at such high densities the models underpredict the strengths of [S II] and [N II] relative to Hα. Single-zone models require n_e ⩽ 10^5 cm⁻³ to match the [N II]/Hα ratios of LINERs and n_e ⩽ 10^4 cm⁻³ for [S II]/Hα.

Agreement with LINER spectra can be achieved with a simple two-zone model, in which high-density and low-density components are present, similar to the scenario proposed by Shields (1992). As an example, a two-component model constructed from grid A containing gas at (n_e = 10^5 cm⁻³, U = 10⁻³³) and at (n_e = 10^4 cm⁻³, U = 10⁻⁴) produces emission-line ratios which are consistent with all the LINER classification criteria of both the Heckman (1980) and Ho et al. (1997a) systems, if the two density components are scaled so as to contribute equally to the total Hβ luminosity. As a local comparison, observations of near-infrared Fe II emission indicate the presence of clouds having n_e > 10^5 cm⁻³ in the Galactic center region (DePoy 1992), so it is plausible that other galactic nuclei may contain ionized gas at similarly high densities even in the absence of an observable AGN. A starburst origin for some LINER 2 nuclei would provide a natural explanation for the lower values of the X-ray/Hα flux ratio seen in these objects, in comparison with AGN-like LINER 1 nuclei (Terashima et al. 1999).

It seems unlikely, however, that many LINERs are generated by this starburst mechanism. About 15% of LINERs are known to have a broad component of the Hα emission line, indicating a probable AGN (Ho et al. 1997b). By analogy with the Seyfert population, a much larger fraction of LINERs is likely to have broad-line regions which are either obscured along our line of sight, or are simply too faint to be detected in ground-based spectra against a bright background of starlight. Many LINERs show signs of nuclear activity that cannot be explained by stellar processes: compact flat-spectrum radio sources or jets, compact X-ray sources with hard power-law spectra, or double-peaked broad Balmer-line emission, for example. As an increasing body of observational work supports the idea that many LINERs are in fact AGNs, there is less incentive to consider purely stellar models for their excitation.

Demographic arguments, similar to those given above for transition nuclei, can be applied for the LINER population. Since the LINER phase only occurs for instantaneous bursts at high density and high metallicity, the starburst scenario implies that H II nuclei should be considerably more numerous than starburst-generated LINERs for a given Hubble type. While LINERs are common in early-type hosts, H II nuclei are not found in elliptical hosts and are seen in fewer than 10% of S0 galaxies (Ho et al. 1997b). This dispar-
ity is a strong argument against a starburst origin for those LINERs in early-type galaxies. In later Hubble types the situation is less clear, however. H II nuclei occur in ~ 80% of spirals of type Sc and later, while LINERs occur in just 5% of these galaxy types (Ho et al. 1997b). It is conceivable that some of the LINERs in intermediate to late-type hosts could have a starburst origin, and this issue could be resolved by further UV and X-ray observations in the future. Interestingly, the Ho et al. survey did not find any examples of broad Hα emission in LINERs or transition objects with hosts of type Sc or later; perhaps star formation plays a more prominent role than accretion-powered activity in these objects.

While a few LINERs show spectral features of young stars in the UV (Maoz et al. 1998), the quality of the observational data is poor in comparison with the NGC 4569 UV spectrum, and it is difficult to set meaningful constraints on the age of the young stellar population. NGC 404 is a possible candidate for a starburst-generated LINER, but in its UV spectrum the P Cygni features are weak in comparison with NGC 4569, indicating either an older burst population or dilution by a featureless AGN continuum (Maoz et al. 1998). The LINERs having UV spectral features from massive stars may also host obscured AGNs which can be detected in other wavebands. For example, the UV continuum of the LINER NGC 6500 appears to have its origin in hot stars (Barth et al. 1997; Maoz et al. 1998), but observations of a parsec-scale radio jet unambiguously demonstrate that nonstellar activity is occurring as well (Falcke et al. 1998).

4.4. W-R Galaxies with LINER or Transition-Type Spectra

The starburst models presented here run into two obvious problems. First, W-R galaxies are almost never known to have LINER or transition-type spectra. Second, LINERs and transition nuclei almost never show W-R features in their spectra. Is there any way to reconcile the starburst models with these facts?

W-R galaxies are identified by the appearance of the 4650 Å blend in their spectra (e.g., Kunth & Sargent 1981). Since the formation of W-R stars is enhanced at high Z, the strength of this feature relative to Hβ increases dramatically with metallicity, from $Z \leq 0.1$ at $Z < 0.4 Z_\odot$ to $\sim 0.5 - 4$ at $Z \geq Z_\odot$ (Schaerer & Vacca 1998). However, in the nuclei of early-type spirals where high metallicities are expected, a nuclear starburst will be surrounded by the old stellar population of the galactic bulge, making the detection of the W-R bump extremely difficult (Mas-Hesse et al. 1999).

Most of the currently known W-R galaxies are late-type spirals or irregular galaxies (Schaerer et al. 1999) in which the W-R bump is visible against the nearly featureless starburst continuum. When the W-R bump is detected in H II galaxies, its amplitude above the continuum level is generally far smaller than that of Hβ or even Hγ (e.g., Kunth & Sargent 1981). In most of the LINER and transition galaxy spectra in the catalog of Ho et al. (1995), however, Hβ barely appears and Hγ is too weak to be visible at all prior to continuum subtraction. Even in a high-metallicity environment, where the total intensity of the W-R bump can be comparable to that of Hβ, the amplitude of the W-R bump above the continuum will be much lower than that of Hβ because the flux in the W-R feature is spread over $\sim 70 - 100$ Å. Thus, the detection of W-R emission in galactic nuclei is strongly biased toward late-type, bulgeless galaxies. In late-type or dwarf irregular galaxies where the W-R bump is visible, the W-R/O-star ratio is expected to be much smaller owing to the lower metallicity, and the resulting softer ionizing spectrum will tend to produce an H II region spectrum rather than a transition object. The gas density as a function of Hubble type may play a role as well; in a study of H II nuclei, Ho et al. (1997c) find a weak trend toward lower nebular densities in later-type host galaxies.

Observational detection of W-R features in transition nuclei is perhaps the clearest test of the starburst models, if sufficiently sensitive observations can be obtained. The UV spectrum of NGC 4569 is consistent with an age of $\sim 3 - 6$ Myr, an age at which W-R stars are expected to be present. Previous optical spectra have not revealed the 4650 Å W-R bump in NGC 4569, but further observations with high S/N and small apertures would be worthwhile. The lack of He II λ4686 emission in the UV spectrum of NGC 4569 is potentially a more serious problem since the burst population should dominate at short wavelengths. The models of Schaerer & Vacca (1998)
predict an equivalent width of at least 2 Å in the W-R-generated λ1640 line during the period 3–6 Myr for an instantaneous burst of solar or higher metallicity, while the observed upper limit of \( f(1640) < 2.0 \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \) (Maiz et al. 1998) corresponds to an equivalent width limit of \( \lesssim 0.3 \) Å. It should be noted, however, that the λ1640 line lies at the extremely noisy blue end of the FOS G199H grating setting, in a region where detection of emission or absorption features is difficult.

Two W-R galaxies may provide useful points of reference for the starburst models. NGC 3367 is classified by Ho et al. (1997a) as an H II nucleus on the basis of its [O III]/Hα and [S II]/Hα ratios, although its [N II]/Hα ratio of 0.83 is more consistent with a LINER or transition-type classification and its emission lines are markedly broader than those of typical H II nuclei. Alonso-Herrero et al. (1999) describe NGC 3367 as a starburst-dominated transition object (see also Dekler et al. 1988). The 4650 Å W-R bump was noted by Ho et al. (1995), who also suggested a LINER/H II classification and a composite source of ionization. As a borderline H II nucleus/transition object with clear evidence for W-R stars, this object deserves further study, to determine whether there is indeed an AGN or whether the enhanced low-ionization emission may be the result of ionization by the W-R population. The electron density of 835 cm\(^{-3}\) measured from the [S II] doublet (Ho et al. 1997a) is also noteworthy, as this is among the highest densities found for an H II nucleus in the Ho et al. survey.

Another intriguing object is the nucleus of NGC 6764, which has been classified variously as a Seyfert, a LINER, and a starburst by different authors (see Gaoncalves et al. 1999). This galaxy exhibits prominent emission in the 4650 Å W-R blend (Osterbrock & Cohen 1982). A recent study by Eckart et al. (1996) demonstrates that the narrow emission lines are consistent with a LINER classification, but there are no unambiguous signs of nonstellar activity in the nucleus. Eckart et al. (1996) find that the nucleus contains ~ 3600 W-R stars, and that the overall properties of the object are consistent with ionization by the starburst alone, rather than by a starburst/AGN composite. If this conclusion is confirmed by further observations, NGC 6764 could be considered the best candidate for a LINER photoionized by a starburst during its W-R-dominated phase. Alonso-Herrero et al. (1999) derived an age of 9–10 Myr for the starburst in NGC 6764 based on near-infrared emission-line diagnostics, but this age is inconsistent with the presence of W-R stars, at least for the case of an instantaneous burst.

Compared with typical LINERs and transition nuclei, conditions for detection of W-R spectral features in these two objects are perhaps more favorable. Both host galaxies are of late Hubble types (Sbc for NGC 3367 and Sb/c for NGC 6764) in comparison with the majority of LINERs and transition nuclei, so the level of contamination by the surrounding old stellar population is relatively low. Furthermore (and partly as a result of this), the emission-line equivalent widths in these two nuclei are relatively high for LINERs or transition nuclei. If the emission-line spectra of NGC 3367 or NGC 6764 had been superposed on a luminous early-type spiral bulge, the W-R emission might never have been noticed.

The detection of W-R emission in a LINER does not automatically imply a purely starburst origin for the emission lines, of course, since starbursts and AGNs are often known to coexist. Mrk 477 is a well-known example of a Seyfert 2 galaxy having a large population of W-R stars in its nucleus (Heckman et al. 1997). In the context of the starburst model, however, the crucial test is to search for additional examples of LINERs or transition nuclei which exhibit a high ratio of W-R to O stars but no signs of accretion-powered activity.

4.5. Caveats and Limitations

The most important limitation of these calculations comes from the accuracy of the input continua. The conclusion that the starburst models are able to reproduce transition or LINER spectra under some circumstances depends crucially on the presence of W-R stars to provide a hard and luminous ionizing continuum. Unfortunately, the continuum shape and luminosity of W-R stars in the extreme-UV band are quite uncertain, particularly in the He\(^{++}\) continuum where stellar winds have a dramatic effect. Several up-to-date reviews of the numerous difficulties involved in modeling W-R spectra can be found in the volume edited by van der Hucht et al. (1999). The STARBURST99 model grid uses the W-R atmospheres
of Schmutz et al. (1992), which are calculated for a pure helium composition, but more recent atmosphere models are beginning to include the effects of line-blanketing, as well as clumping and departures from spherical symmetry. As discussed by Leitherer et al. (1997), the W-R/O-star ratio is also extremely model dependent, and may be revised in future generations of models. This would have a direct effect on the strength of the extreme-UV continuum and consequences for the nebular emission lines. Furthermore, the STARBURST99 models neglect binary evolution, although this is more likely to affect the W-R/O ratio at low metallicity. Since the results of the transition-object models are highly dependent on the most uncertain portion of the W-R spectrum, new photoionization calculations should be computed to assess the impact of different W-R evolution and atmosphere models in the future.

The shape of the IMF in starburst regions is a subject of some debate, and the possible variation of the IMF with metallicity is of particular importance for galactic nuclei, which are likely to have \( Z \gtrsim Z_\odot \). Kuhn (1974) and Shields & Tinsley (1976) suggested that \( M_{\text{up}} \) should be lower in regions of higher metal abundance, but this issue has not been settled definitively. Star-count observations demonstrate that the IMF slope and \( M_{\text{up}} \) do not appear to vary with metallicity (Massey et al. 1995), at least for \( Z \lesssim Z_\odot \). While nebular diagnostics in H II galaxies are generally consistent with a Salpeter IMF with \( M_{\text{up}} \approx 100 M_\odot \) at subsolar metallicity (e.g., Stanislawa & Leitherer 1996), at high metallicity the observational situation is somewhat ambiguous. Bresolin et al. (1999) find that the mean stellar temperature in H II regions decreases significantly with increasing \( Z \), and that the He I \( \lambda5876 / \text{H} \beta \) ratios of H II regions at \( Z \approx 2Z_\odot \) are more consistent with \( M_{\text{up}} = 30 M_\odot \) than with \( M_{\text{up}} = 100 M_\odot \). Such a low value for \( M_{\text{up}} \) would pose serious difficulties for any starburst models of LINERs and transition nuclei, as the massive progenitors of W-R stars would not be present. Counterbalancing this trend, the strong tidal forces, turbulence, and magnetic field strengths in galactic nuclei may act to raise the Jeans mass and favor the formation of more massive stars (Morris 1993). In the Galactic center, there are stars with initial masses of \( \sim 100 M_\odot \) (Krabbe et al. 1995), and one Galactic center object (the Pistol star) may have \( M_{\text{initial}} \) as high as 200–250 \( M_\odot \) (Figer et al. 1998). Thus, the proposed trend toward lower values of \( M_{\text{up}} \) at high metallicity in disk H II regions may not apply to galactic nuclei. Detailed comparison of the UV spectra of galaxies such as NGC 4569 with starburst population synthesis models can provide useful constraints on the population of high-mass stars in nuclear starbursts.

Despite these uncertainties, these photoionization models have a major advantage compared with previous generations of W-R or O-star models for LINERs and transition nuclei, in that the STARBURST99 models with standard parameters are constructed to represent the actual stellar populations in starbursts, to the best of current knowledge. Previous O-star models (Filippenko & Terlevich 1992; Shields 1992) required the presence of hypothetical, unusually hot stars in order to explain LINER or transition spectra, and they did not address the evolution of the young stellar population at all. The starburst models presented here provide a more plausible mechanism to generate a transition-type spectrum, even if this model may apply only to a relatively small fraction of the population of transition galaxies.

5. Conclusions

Our primary conclusion is that for standard starburst parameters and for nebular conditions which may be typical of galactic nuclei, the starburst models are able to reproduce the important diagnostic emission-line ratios for LINER/H II transition galaxies, otherwise known as weak [O I] LINERs. The key ingredient needed to generate a transition-type spectrum is a UV continuum dominated by W-R stars, a condition which occurs during \( t = 3–5 \) Myr after an instantaneous burst. A transition-type emission spectrum may thus be a phase in the evolution of some nuclear H II regions in which the ionizing continuum is generated by a single-burst stellar population. The models are also able to produce an [O I] / H\alpha ratio high enough to match LINER spectra, but only for conditions of above-solar metallicity combined with the presence of high-density \( \gtrsim 10^5 \) cm\(^{-3}\) clouds. A sensitive search for W-R spectral features in transition nuclei would provide a test of this starburst scenario. This model may
apply only to a small fraction of LINERs and transition nuclei; many LINERs and some transition objects show clear signs of nonstellar activity, and the starburst models may not apply at all to objects in early-type host galaxies. Further multi-wavelength observations of transition nuclei will be of great utility for determining what fraction of them contain genuine active nuclei, and what fraction appear to be purely the result of stellar phenomena.

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### Table 1
**Model Parameters**

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**Note.**—All models listed above are calculated for $M_{\text{up}} = 100 \, M_\odot$, IMF power-law slope of $-2.35$, and for plane-parallel nebular geometry. The star-formation law in Column 2 denotes I = instantaneous burst, and C = constant star-formation rate. The metallicity $Z$ refers to the stars and to the undepleted abundance of the nebular gas.
Figure Captions

Fig. 1.— Line-ratio diagram of [O III] $\lambda 5007$ / H$\beta$ against [O II] $\lambda 3727$ / H$\alpha$, for model grids A (solid line), B (long-dashed line), C (short-dashed line), and D (dot-dashed line), at a burst age of 4 Myr and $n_e = 10^3$ cm$^{-3}$. The input continuum has solar metallicity, IMF power-law slope $-2.35$, and $M_{\text{dep}} = 100$ $M_\odot$. The following description applies to this and all subsequent plots: the small squares along each model line correspond to the model grid points at $U = -4, -3.5, -3, -2.5$, and -2, with $U$ increasing upward along the line. The points plotted represent galaxies from the Ho et al. catalog, as follows: Small circles: H II nuclei. Squares: LINER/H II transition objects. NGC 4569 is represented by an open square. Triangles: “pure” LINERs. Crosses: Seyfert nuclei. The dotted line encloses the region defined for transition nuclei according to the criteria of Ho et al. (1997a).

Fig. 2.— Same as Figure 1, but for the line ratio [N II] $\lambda 6583$ / H$\alpha$. The dotted line encloses the region occupied by both LINERs and transition objects, according to the criteria of Ho et al. (1997a).

Fig. 3.— Same as Figure 1, but for the line ratio [S II] $\lambda\lambda 6716, 6731$ / H$\alpha$. The dotted line encloses the region occupied by both LINERs and transition objects, according to the criteria of Ho et al. (1997a).

Fig. 4.— Density effects on the [O I] $\lambda 6300$ line strength, for model grid A. Plot symbols for individual data points are the same as for Figure 1. The model sequences are shown for age 4 Myr and nebular density of $\log (n_H/cm^{-3}) = 2, 3, 4, 5, $ and 6.

Fig. 5.— Burst age effects on the [O I] $\lambda 6300$ line strength, for model grid A. Plot symbols are the same as for Figure 1. The model sequences are shown for nebular density $n_e = 10^3$ cm$^{-3}$ and burst ages of 2, 3, 4, 5, and 6 Myr.

Fig. 6.— Burst age effects on the [N I] $\lambda 6583$ line strength, for model grid A. Plot symbols are the same as for Figure 2. The model sequences are shown for nebular density $n_e = 10^3$ cm$^{-3}$ and burst ages of 2, 3, 4, 5, and 6 Myr.

Fig. 7.— Burst age effects on the [S II] $\lambda\lambda 6716, 6731$ line strength, for model grid A. Plot symbols are the same as for Figure 3. The model are shown for nebular density $n_e = 10^3$ cm$^{-3}$ and burst ages of 2, 3, 4, 5, and 6 Myr.

Fig. 8.— Metallicity effects on the [O I] $\lambda 6300$ / H$\alpha$ flux ratio. Plot symbols are the same as for Figure 4. Model grids are plotted for the cases of $Z/Z_\odot = 0.2$ (dot-dashed line; from grid E), 0.4 (long-dashed line; from grid F), 1 (solid line; from grid A), and 2 (short-dashed line; from grid G). Each sequence is shown for $n_H = 10^3$ cm$^{-3}$ and $t = 4$ Myr.

Fig. 9.— The [O I] $\lambda 6300$ / H$\alpha$ flux ratio for the case of $Z = 2Z_\odot$ (model grid G), at $t = 4$ Myr. Plot symbols are the same as for Figure 4. The model sequences are plotted for densities of log $(n_H/cm^{-3}) = 3, 4, 5, $ and 6.