THE IONIZED GAS IN THE CENTER AND IN THE BAR OF THE SPIRAL GALAXY NGC 6946

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ABSTRACT

Spectrophotometric data based on narrow-band images at Hα, Hβ, [O III] λ5007 and [N II] λ6584 for 189 H II regions in the spiral galaxy NGC 6946 are presented, with emphasis on the inner regions (R ≤ 2.5 kpc). The properties of the ionized gas are compared with those of the CO molecular bar. The possible influence of the bar on the ionized interstellar gas and star formation is discussed. The relatively high number of H II regions in the center is consistent with an enhancement of massive star formation as revealed by infrared and molecular observations; the molecular gas bar in NGC 6946 is a favorable environment for massive star formation. The excitation and abundance indicators ([O III] (λ5007 + 4959)/Hβ and [N II] (λ6584 + 6548)/[O III] (λ5007 + 4959)) show an unusual behavior as a function of galactocentric distances, and their radial trend is consistent with a flattening of the global O/H gradient in the inner regions of NGC 6946. This may be evidence of dilution by low-metallicity gas from outer regions due to strong radial flow along the molecular bar.

Subject headings: galaxies: ISM — galaxies: individual (NGC 6946) — galaxies: spiral — H II regions — ISM: abundances — ISM: molecules

1. INTRODUCTION

The presence of nonaxisymmetric features in the distribution of gas and stars in the inner regions of galaxies is a common occurrence in a majority of disk galaxies for which detailed radio and optical observations have been obtained. Huntley, Sanders, & Roberts (1978) and Roberts, Huntley, & van Albada (1979) made the dramatic demonstration of how a slight oval distortion, such as a weak rotating barlike perturbation, in the gravitational potential will form a central gas bar with trailing spiral waves. This pattern may survive through many galaxy rotations (Combes & Gerin 1985) and can affect the evolution of the gas through its effect on the gas. Indeed, the presence of a bar gives rise to processes (shocks, radiation, magnetic fields) which, in addition to gravity, influence the distribution and the dynamics of interstellar gas. Roberts et al. (1979), Combes & Gerin (1985), England (1989), and Athanassoula (1992), for example, have shown that the bar perturbation will strongly interact with the rotating disk gas; shocks develop, and after losing angular momentum, the gas sinks toward the center while some is driven outward beyond the corotation radius. Thus star formation would be favored at certain locations such as at the bar ends due to an orbit crossing effect (Kenny & Lord 1991). The nuclear regions will also be favored as shown by Arsenault (1989) who found a high preponderance of bars and ring features in starburst galaxies. However, because of stronger tidal forces and more frequent cloud-cloud collisions, star formation may also be quenched in bars (Waller & Hodge 1991; Kenney & Lord 1991). Therefore, one may find bars, or regions of bars, where star formation is enhanced, and others where it is inhibited.

Bars can induce strong radial flow in the interstellar gas of a galaxy. The various aspects of the hydrodynamics of galaxy disks under the conditions of radial flow have been investigated; see, for example, Mayor & Vigroux (1981), Lacey & Fall (1985), Clarke (1989, 1991), Edmunds (1989, 1990), and Struck-Marcell (1991) where related work is also cited. These studies indicate that radial flows should modify the local element composition in galaxies. Therefore, abundance gradients could hide some of the history of interstellar gas circulation. Alloin et al. (1981) have already noted the "mild abundance gradient" of the spectacular southern barred spiral galaxy NGC 1365. In a recent paper (Belley & Roy 1992), we suggested that the O/H abundance gradient in the galaxy NGC 6946 may be flatter in the inner regions, i.e., for R ≤ 0.5R_{eff}. We have reexamined our optical narrow-band imagery of NGC 6946 to increase the number of H II regions with spectroscopic data in order to ascertain the radial trends in the inner regions of this galaxy. For a more complete view of the interstellar gas processes and star formation, we have also compared our optical data with a recent CO map published by Kawabe et al. (1991). In the present paper, we propose that the behavior of nebular lines indicates dilution of the central interstellar gas by low-metallicity gas from outer regions.

NGC 6946 is a large Scd late-type spiral galaxy which displays moderate starburst activity (de Gioia-Eastwood et al. 1984; Engargiola 1991). Quoted values for its distance vary from about 5 to 10 Mpc. We have adopted the value of 5.9 Mpc (McCall 1982), giving a scale on the sky of 28.7 pc arcsec^{-1}; we used the value of R_{eff} = 6.23 kpc from the same source as the effective radius of the disk (for a face-on galaxy, this is the radius of a circular aperture containing half of the total light of the disk). The galaxy has been studied extensively at optical and radio wavelengths, and only the most recent studies are quoted here; overviews of several other works can be found in Tacconi (1988), Weiachew, Casoli, & Combes (1988), and Engargiola (1991). The most recent H I distribution maps have been published by Tacconi & Young (1986) and Carignan et al. (1990). Because of its near distance and large angular size, the galaxy has been a favored target for CO observations (Ball et al. 1985; Tacconi 1988; Weiachew et al. 1988).
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3. RESULTS

3.1. The Hα and CO Connection

The most striking feature of the ionized gas in the inner regions of NGC 6496 is its close association with the molecular gas as traced by CO. We have compared our Hα image with the fine CO (J = 1−0) map obtained by Kawabe et al. (1991) using the Nobeyama Millimeter Array with 3′0/3′5 resolution. Figure 2a (Plates 3–4) show a superposition of the CO intensity contour map on the Hα monochromatic image of the galaxy of Figure 1a. Figure 3c (Plates 5–6) shows the superposition of the CO contour map on the red continuum image of NGC 6496. The CO isovelocities contours superposed on the Hα and continuum images are shown in Figures 2b and 3b. The coincidence between the CO bar and the bright chain of H II regions north of the nucleus is striking. The tight contours in the velocity maps are consistent with a flow of the ionized gas and molecular gas along the axis of the bar. Kawabe et al. (1991) have suggested that the strong central enhancement in CO (diameter ∼ 320 pc) is caused by a massive nuclear disk of molecular gas fed by gas inflow along the bar. The CO feature could also arise from an unresolved ring of molecular clouds which can develop in systems with a low angular velocity bar as shown in the numerical simulations of Combes & Gerin (1985). The ionized and molecular gas morphology in NGC 6496 is reminiscent of a similar pattern of the interstellar gas observed in the central region of M101 by Kenney, Scoville, & Wilson (1991).

There is excellent coincidence between the star forming regions, as revealed by our Hα observations, and the molecular gas as observed by Kawabe et al. (1991): the strongest Hα emission falls on the western slope of the molecular bar, while the CO crest matches reasonably well the strongest absorption zones seen in the stellar continuum images (Figs. 1b and 3a). There is a tight relationship between some of the ionized gas, molecular gas, stars, and dust in NGC 6496. This sort of relationship is not always very obvious in galaxies explored thus far; see the work of Lord & Kenney (1991) who discuss the case of M83 where CO is closely associated with H II regions, in contrast with M51 where CO emission peaks in the dust lanes. The association of molecular gas, as revealed by CO, and formation of massive stars is an intricate affair. Massive star formation in the molecular bar of NGC 6496 is a striking contrast with the bar of the galaxy NGC 4303 which is devoid of H II regions (Martin & Roy 1992).

3.2. Radial Trends: Line Ratios and Emission Equivalent Widths

Assuming the existence of a statistical relationship between the effective temperature of the hottest stars in the ionizing clusters, one can use the line ratios [O iii]/Hβ and [N ii]/[O iii] as abundance indicators (Edmunds & Pagel 1984). The global changes of [O iii]/Hβ or of several other diagnostic line ratios across the face of late-type galaxies are mainly driven by abundance changes (Searle 1971). Such ratios are used to guess abundances where T_e-sensitive lines like [O iii] λ4363 or [N ii] λ5755 are too weak to be detected. These two ratios are sensitive to T_e which is set by the rate of heating and cooling; cooling depends mostly on the oxygen content. At high metallicity, [N ii]/[O iii] is high and [O iii]/Hβ is low; thus a gradient in the strength of the above line ratios is observed in galaxies with strong change of abundance across their disks.

The radial trends of [O iii]/Hβ and [N ii]/[O iii], for the sample of 189 H II regions in NGC 6496, as a function of...
Fig. 1a

Fig. 1.—(a) CCD monochromatic Hα image of the galaxy NGC 6946 obtained with the 1.6 m telescope of Mont Mélangic Observatory. The field shown is approximately 3.7 × 4.8 arcmin². North is at the top, and east at left. (b) Continuum image at 7020 Å (Δλ = 200 Å). Field and orientation are the same as in (a); the white cross indicates the position of the galaxy center.

Roy & Belley (see 406, 61)
Fig. 2a

Fig. 2.—Superposition of the CO contour intensity map (a) and of the CO isovelocity contours (b) obtained by Kawabe et al. (1991) on the Hα image of the center of the galaxy NGC 6946. Contour intervals on the CO intensity map are 55 K km s⁻¹; dotted contours are negative.

Roy & Belley (see 406, 61)
Fig. 2b
FIG. 3a

Fig. 3.—Superposition of the CO contour map (a) and of the CO isovelocity contours (b) obtained by Kawabe et al. (1991) on a red continuum image of the center of the galaxy NGC 6946. A thick line shows an isovelocity contour at the systemic velocity, $V_{LSR}$, of 60 km s$^{-1}$, and contour interval is 10 km s$^{-1}$. Contours are as in Fig. 2.

ROY & BELLEY (see 406, 61)
PLATE 6

FIG. 3b

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galactocentric distances are shown in Figure 4, where the black symbols correspond to H II regions associated with the molecular bar. Except for one, all H II regions have typical line ratios, that is their spectra correspond to a gas photoionized by OB stars. One H II region very close to the nucleus (No. 163 in Belley & Roy 1992) is characterized by both high values of \([\text{O iii}] / \text{H}\beta\) and \([\text{N ii}] / \text{H}\alpha\) which is indicative of nuclear activity; the point for this region is shown within parentheses in Figures 4 and 5, and will not be used for abundance calculation. The trends of \([\text{O iii}] / \text{H}\beta\) and \([\text{N ii}] / \text{O iii}\) versus \(R / R_{\text{eff}}\) show a flattening in the inner regions \((R \leq 0.4 R_{\text{eff}} = 2.5\) kpc) of NGC 6946. This is in contrast with the central regions of NGC 628, a large spiral galaxy without bar, where there is a monotonic increase of \([\text{N ii}] / \text{O iii}\) and decrease of \([\text{O iii}] / \text{H}\beta\) continuing until the center of the galaxy (Belley & Roy 1992; see their Figs. 12 and 13).

We have explored simple linear fits to the data points. We list the appropriate equations and correlation coefficients for different fits to the radial trends in Table 1; \(y\) corresponds to the relevant line or abundance ratio and \(x\) is the galactocentric distance in units of \(R / R_{\text{eff}}\). The two-segment fit is for the range of the bar, i.e., \(R \leq 0.4 R_{\text{eff}}\), and for the range beyond the bar, i.e., \(0.4 \leq R \leq 1.4 R_{\text{eff}}\). The coefficients of correlation for the range corresponding to the bar are always small, consistent, with very little slope or no gradient at all; beyond the range of the bar, the coefficients of correlation are high (Table 1), and we have plotted the fit for this segment only in Figures 4 and 6. The ranges of \(R / R_{\text{eff}}\) where we have applied the fits are different; they stop at \(R = 1.1 R_{\text{eff}}\) for \([\text{N ii}] / \text{O iii}\) because the sampling of H II regions in the \([\text{N ii}]\) line is incomplete due to a mismatch of the observed fields. Sampling was complete to \(R = 1.4 R_{\text{eff}}\) in \([\text{O iii}] / \text{H}\beta\). We note, however, that the \([\text{N ii}] /
IONIZED GAS IN NGC 6946

TABLE 1

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Radial Range (R/R_{\text{eff}})</th>
<th>Equation</th>
<th>Coefficient of Correlation</th>
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</thead>
<tbody>
<tr>
<td>log [N II]/[O III]</td>
<td>0–1.1</td>
<td>y = -(1.04 \pm 0.25)x + 1.04</td>
<td>0.68</td>
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<tr>
<td>log [O III]/H\beta</td>
<td>0–1.4</td>
<td>y = -(0.87 \pm 0.04)x + 0.87</td>
<td>0.68</td>
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<td>12 + log (O/H)_{\text{A}}</td>
<td>0–1.1</td>
<td>y = -(0.38 \pm 0.02)x + 9.245</td>
<td>0.67</td>
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<tr>
<td>12 + log (O/H)_{\text{B}}</td>
<td>0–1.4</td>
<td>y = -(0.47 \pm 0.024)x + 9.291</td>
<td>0.67</td>
</tr>
</tbody>
</table>

One-Segment Correlations versus R/R_{\text{eff}}

<table>
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<tr>
<th>Ratio</th>
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<th>Equation</th>
<th>Coefficient of Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>log [N II]/[O III]</td>
<td>0–0.4</td>
<td>y = -(0.48 \pm 0.058)x + 0.884</td>
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<td>0–1.1</td>
<td>y = -(1.21 \pm 0.072)x + 1.196</td>
<td>0.62</td>
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<tr>
<td>log [O III]/H\beta</td>
<td>0–0.4</td>
<td>y = -(0.31 \pm 0.012)x + 0.665</td>
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</tr>
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<td></td>
<td>0–1.4</td>
<td>y = -(0.90 \pm 0.035)x + 0.985</td>
<td>0.74</td>
</tr>
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<td>y = -(0.11 \pm 0.033)x + 9.169</td>
<td>0.11</td>
</tr>
<tr>
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<td>0–1.1</td>
<td>y = -(0.46 \pm 0.027)x + 9.298</td>
<td>0.61</td>
</tr>
<tr>
<td>12 + log (O/H)_{\text{B}}</td>
<td>0–0.4</td>
<td>y = -(0.12 \pm 0.094)x + 9.157</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>0–1.4</td>
<td>y = -(0.60 \pm 0.021)x + 9.402</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Two-Segment Correlations versus R/R_{\text{eff}}


* O/H derived from the [O III]/H\beta ratio calibrated by Edmunds & Pagel 1984.

[O III] data points at R/R_{\text{eff}} \geq 1.1 are systematically high, a behavior which is not reflected in the [O III]/H\beta data set.

Only a few other well-sampled external galaxies exist. Although they may have fewer points, the trends in these galaxies are consistent with monotonic change of [N II]/[O III] and [O III]/H\beta with radius (cf. Zaritsky, Elston, & Hill 1989, 1990; Walsh & Roy 1989; Belley & Roy 1992; Scowen, Dufour, & Hester 1992) find a change in the slope of the [O III]/H\beta trend in the outer parts of the galaxy M101. We propose that the flattening of nebular line ratio gradients observed in the inner regions of NGC 6946 is significant.

The dispersion of the values of [O III]/H\beta at any given radius is large and appears greater than those of [N II]/[O III]. This may reflect the highly variable conditions responsible for the enhancement of the O^+ zone in the H\alpha regions. Indeed [O III]/H\beta is not only affected by the abundance of oxygen in the interstellar gas but is also sensitive to T_e, the characteristic temperature of the stellar radiation field, and to the ionization parameter which depends on the geometry and distribution of the gas (McCull et al. 1985; Dopita & Evans 1986; Edmunds & Pagel 1984; Evans 1991). It is very difficult to single out abundance variations, because of the unknown behavior of familiar abundance indicators as a function of O/H in the high abundance regime such as probably exists in the inner regions of galaxies (Stasinskas 1990; Evans 1991; Rubin 1989). We will come back to this point later.

Both the H\beta and H\alpha equivalent widths measure the relative fraction of O stars to lower mass stars, which contribute more to the visible light. There have been suggestions that EW(H\alpha) decreases near the central bulge due to a significant decrease in the initial upper stellar mass limits of the ionizing clusters (e.g., Waller & Hodge 1991). EW(H\beta) and EW(H\alpha) are sensitive to

![Graph 1](https://via.placeholder.com/150)

**Fig. 6a**

The gradient in oxygen abundance across NGC 6946, calculated using (a) the calibration of [O III]/H\beta and (b) of [N II]/[O III] by Edmunds & Pagel (1984). The black symbols correspond to the H\alpha regions in the bar. The solid line represents a linear fit to the data points for the H\alpha regions beyond the bar (R \geq 0.4R_{\text{eff}}), where the coefficient of correlation is high, for a two-segment fit (see Table 1).
both the IMF and to the history of star formation (Copetti, Pastoriza, & Dottori 1986; Olofsson 1989). Assuming the nebula continuum to have a negligible contribution, we measured EW(Hβ) and EW(Hα) of the H II regions in NGC 6946. This is difficult to measure because of the necessity of subtracting the contribution of general disk emission which is stronger in the inner parts of the galaxy. In order to take into account contamination by the background stellar light, we subtracted an amount of continuum light measured over an adjacent area with an aperture of the same size as that used for each H II region and at the same radial distance. This subtraction is important; indeed, our tests revealed that if one does not subtract this background, a strong decrease of EW(Hβ) in the central regions is artificially produced. As shown in Figure 5b, values of EW(Hβ) are relatively high in the center of NGC 6946; this is not unexpected in view of the unusual star-forming activity found there. At any given radius, the spread in EW is considerable (possibly reflecting ionizing star cluster age differences), and there appears to be a lack of high values of EW(Hα) in the center (Figure 5a). Because of the impossibility of accurately removing contaminating stellar continuum, the local behavior of EW should be interpreted with caution.

4. DISCUSSION

We have already suggested that the flattening of the radial trends of [O III]/Hβ and [N II]/[O III] near the center of NGC 6946 is related to processes associated with the bar of interstellar gas. Comparing Figures 4a and 4b, [N II]/[O III] displays the apparent “flattening” in the center of NGC 6946 in a clearer way than [O III]/Hβ because of its much smaller scatter. Several effects influence the line ratios [O III]/Hβ and [N II]/[O III]. We discuss first the reasons for the large scatter of [O III]/Hβ in the inner regions.

4.1. Factors Affecting [O III]/Hβ and [N II]/[O III]

The [O III]/Hβ ratio involves one collisionally excited line and one recombination line, while the ratio of two collisionally excited lines is used in [N II]/[O III]. The fact that similar physics enters in [N II] and [O III] explains in part the smaller scatter of [N II]/[O III] in radial trends. The strength of [O III] depends on abundance, but is also related to the relative size of the O+ + zone; this depends on the shape of the ultraviolet spectrum of the ionizing stars. Evans (1991) has explored this aspect in detail by computing theoretical H II region models with various stellar atmosphere models. One of the conclusions of his work is particularly relevant to the behavior of line ratios in the center metal-rich regions of galaxies. For H II regions ionized by cooler stars (low Te) or which are only weakly ionized [low values of the ionization parameter, (Q(H))], the volume ratios of O+/O+ + are extremely sensitive to small changes of these parameters. Consequently the [O III] λ5007 strength is expected to be highly dependent on the atmospheric metallicity for low Te. Therefore, the high metallicity of both gas and ionizing stars amplify fluctuations of [O III]/Hβ. Finally, observed line intensities correspond to integration through the emitting volume, and the density structure along the line of sight in the nebula will also affect the relative strengths of nebular lines (cf. Rubin 1989). These dependencies of [O III]/Hβ on Te, Q(H), and Ne explain in good part the dispersion of [O III]/Hβ or of other line ratios observed at any given radius where one expects little azimuthal variation in abundance, and why the dispersion of [O III]/Hβ is significantly larger in the inner regions of NGC 6946.

Compared with NGC 628, there are many more H II regions in the center of NGC 6946, and the total gas surface density is also much higher in NGC 6946 (Struck-Marcell 1991). As just discussed, the large dispersion of [O III]/Hβ values in the central parts of NGC 6946 is probably due to the relative range of metallicities of the ionizing stars and/or of the ionizing parameters. It is impossible to discriminate between these two factors with the present data only. If one compares the diagnostic diagram [N II]/Hα versus [O III]/Hβ of the inner H II regions of NGC 6946 with nebular models ionized by a Kurucz (1979) line-blanketed LTE stellar atmosphere calculated by Evans (1991), one finds that the majority of the inner H II regions of NGC 6946 cluster around low T_e (≈ 37,000 K) and ionization parameters. This is consistent with what one expects for the high-Z interstellar medium of centers of galaxies (Dopita & Evans 1986).

4.2. Equivalent Widths of Hβ and Hα

Figures 5a and 5b illustrate the radial behavior of EW(Hα) and EW(Hβ) in NGC 6946. The most simple explanation is that the lower values of EW as one approaches the center are due to the relatively stronger continuum flux in the inner regions than at larger radial distances. The continuum around Hβ is strongly dependent on the IMF of the ionizing association due to the dominant contribution of the less massive stars. In their spectrophotometric survey of 99 extragalactic H II regions belonging to 20 galaxies, McCaill et al. (1985) found that the absolute surface brightness of the continuum at Hβ is systematically higher in high-abundance objects than in low-abundance objects; two typical spectra shown in Figure 1 of McCaill et al. are a fine illustration of this effect. Since the surface brightness of Hβ emission does not vary substantially with abundance, McCaill et al. have proposed that the trend in emission equivalent widths must be caused entirely by variation in the continuum level; there is a class of stars that contribute significant amounts of optical continuum, but little ionizing flux, whose fractional population increases with the metal abundance. This is clearly seen in the decreasing height of the upper envelope of EW(Hβ and Hα) as one approaches the center of NGC 6946.

H II regions are present right to the center of NGC 6946; the molecular bar of NGC 6946 is a favorable site for star formation, that is when the molecular clouds fall into the bar potential, they are more likely to coalesce than to be disrupted. Nevertheless, as stated in the Introduction, bars could also inhibit star formation. There appears to be a threshold in the set of physical parameters of a bar which determines whether star formation will take place or not. Bars can be accompanied by shocks in the gas with very strong shears. However, if the bar is weak, clouds will have time to collapse before being sheared out as suggested by Athanassoulas (1992). She has also published interesting results of numerical simulations showing that galaxies with ovales or weak bars have more curved dust lanes than galaxies with strong bars where dust lanes are straight. The curved shape of the dust lanes in the center of NGC 6946 as seen in Figure 1b is consistent with a weak bar; thus star formation is enhanced.

4.3. O/H Abundances

The inferred values of O/H given by the empirical method are somewhat uncertain, especially in the center of galaxies where abundances are high compared to solar ones. This is because the derivation of O/H in H II regions with metallicities
near or above solar is obtained indirectly by using semi-empirical calibrations extrapolated to values far above the highest metallicity for which data exist, and where the relation depends on photoionization models alone. Because of differences of assumption and approaches, calibrations differ in their predictions although the ranking of H II regions according to abundance is good: Compare, for example, the calibrations of the ([O III]/Hβ) versus 12 + log O/H as proposed by Edmunds & Pagel (1984), McCall et al. (1985), or Dopita & Evans (1986). Differences can also be fully appreciated by looking at examples of application of such calibrations as presented in Shaver et al. (1983), Evans (1986), Dopita & Evans (1986), Garnett & Shields (1987), Zaritsky et al. (1989, 1990), Walsh & Roy (1989), Martin & Roy (1992) and Vila-Costas & Edmunds (1992).

Dopita & Evans (1986) have demonstrated that [N II]/[O III] is an excellent T_e indicator in the O ++ zone especially at the high-abundance end. At low abundances, the scatter of [N II]/[O III] versus T_e increases; this is attributed to more nitrogen being of primary origin at low abundances. Using the calibrations of [N II]/[O III] and [O III]/Hβ versus O/H by Edmunds & Pagel (1984), we have derived O/H for the ensemble of the H II regions in NGC 6946 (the central region No. 163 has been excluded). The abundance gradients are shown in Figures 6a and 6b; dispersion at any given radius is high especially for O/H derived from [O III]/Hβ, but the gradient flattening in the central region is obvious for the O/H values derived from [N II]/[O III]. Parameters of the various fits are given in Table 1. Because of the very small correlation coefficients for R < 0.4R_eff (Table 1), the two-segment linear fit (full lines) is more appropriate than a one-line segment fit; the trend for 0 ≤ R/R_eff ≤ 0.4 is consistent with a flat gradient, and only the segment having a significant coefficient of correlation is drawn in Figures 6a and 6b. There is also an apparent flattening beyond R ≥ 1.1R_eff for log O/H derived from the [N II]/[O III] indicator. However, as warned above, sampling at large radial distances is incomplete in [N II]. At this stage, we can assume only a monotonic decrease and emphasize the need for more observations with a larger field of view.

In Figure 7, we display in a different way the O/H gradient in NGC 6946 as compared with those of the ordinary galaxies NGC 628 and NGC 2997; the reader should note that the O/H gradients of these two galaxies are similar within the uncertainties (see Belley & Roy 1992). For NGC 6946, we have taken the mean of values of [O III]/Hβ and [N II]/[O III] for all H II regions in increasing radial annuli of width ΔR = 0.1R_eff. We then derived O/H for both indicators from these means. The agreement between the two indicators is good except at larger R where [N II]/[O III] leads to higher values. The flattening of the O/H gradient in the center of NGC 6946 is obvious.

4.4. Dilution by Radial Flows

Can radial transfer of interstellar gas along the bar modify the relative abundances in the inner regions? Self-diffusion depends on the mean free path and mean random velocity of the gas element and has a very long time scale; it will not be an important contributor to the redistribution of elements across the disk (Struck-Marcell 1991). Hydrodynamic equilibrium in the disk will tend to maintain a 1/r surface density profile for the gas. If rapid consumption through star formation or ejection depletes the gas in the inner regions, a steady gas inflow could balance that consumption (Struck-Marcell 1991), if the sound crossing time in the disk is less than or equal to the star formation time scale.

In NGC 6946, the 1/r gas surface density profile is maintained despite a vigorous star formation rate in the central regions (de Gioia-Eastwood et al. 1984). Obviously the inward flow of gas is capable to maintain the 1/r gas profile; the molecular bar probably visualizes this flow (Kawabe et al. 1991), and some ionized gas is also entrained (Bonnarel et al. 1988). Struck-Marcell (1991) discusses the particular case of NGC 6946 as a galaxy where the noncircular velocity field may drive a radial flow of v_r ≥ 10 km s^{-1}. Following his arguments, if the gas cannot be consumed through star formation (or ejection) as fast as it flows in, the local interstellar medium becomes diluted with low-metallicity gas; the mean level of O/H abundances in the interstellar medium also becomes lower than in galaxies where radial flows are absent (e.g., a galaxy like NGC 628 which shows a surface density gas profile depleted in comparison to a 1/r profile in its inner regions). More gas is brought in than can be consumed, and dilution takes place.

To check the physical consistency of the idea, we evaluate the time scale required to bring a given amount of low-metallicity gas from the outer parts of the disk to account, by dilution, for the reduced abundances in the central regions. Using the [N II]/[O III] abundance indicator and extrapolating the indicated line of correlation to the center (Fig. 6b), one can estimate the O/H depletion to be about 0.1–0.2 dex in O/H compared to a normal rising abundance profile right to the center. The total mass of gas present in the inner 2.5 kpc of NGC 6946 is ~ 10^8 M_s, assuming a mean surface density of 100 M_s pc^{-2} for the gas (Struck-Marcell 1991). To compensate for gas consumed in forming new stars, feeding a possible active nucleus, or being expelled by a galactic wind, we need to replenish this gas with gas orbiting farther away in the disk, thus having lower metallicity. The bar potential is an effective pump for driving the required radial flow; such a flow is very likely present in NGC 6946. Following Struck-Marcell (1991), we model the inflow by an azimuthally averaged radial velocity.
ν_r. Mass conservation in the center requires that
\[ \Sigma \nu_r(2\nu_r) = \nu_r \rho^2 + M_\text{expel}, \]
where \( \Sigma \) is the gas surface density, \( \nu_r \) is the star formation rate in units of mass per unit area per unit time, and \( M_\text{expel} \) is the rate of mass loss due to expulsion from the center in the galactic wind or fountain.

Star formation in NGC 6946 has been thoroughly studied by de Groot-Eastwood et al. (1984). From their results, it can be estimated that \( \sim 60 \ M_\odot \ pc^{-2} \ Gyr^{-1} \) in massive stars are being formed in the inner 2.5 kpc radius (for a distance of 5.9 Mpc). Again following Struck-Marcell (1991), one can show that gas radial flow could maintain a star formation rate of
\[ \psi \approx 2000 \ \left( \frac{\Sigma}{100 \ M_\odot \ pc^{-2}} \right) \left( \frac{\nu_r}{10 \ km \ s^{-1}} \right) \left( \frac{1 \ pc}{r} \right) \frac{M_\odot}{Gyr \ pc^2}. \]

Taking the gas pressure of the radial flow at 3 kpc to be \( \sim 50 \ M_\odot \ pc^{-2} \) (Struck-Marcell 1991), one finds that a radial flow of strength \( \nu_r \) could sustain a star formation rate of \( \psi = 40(\nu_r/10 \ km \ s^{-1}) \ M_\odot \ pc^{-2} \ Gyr^{-1} \). This rate is azimuthal symmetry in the radial flow. However, we know that radial flows in barred galaxies are funneled along the bar; therefore assuming that the flow covers a sector corresponding to only 10\% of the disk, it could still transport \( \sim 40(\nu_r/10 \ km \ s^{-1}) \ M_\odot \ pc^{-2} \ Gyr^{-1} \) of outer gas into the inner regions. Thus one needs a radial flow along the bar of about 15 km s\(^{-1}\) to compensate for the observed SFR. A stronger flow will contribute to dilute the enriched material ejected from the evolved stars; with \( \nu_r = 30 \) km s\(^{-1}\), the inner gas could be completely recycled in roughly \( 5 \times 10^9 \) yr. We propose that the observed flattening of the O/H abundance gradient in the center of NGC 6946 betrays such a diluting flow. An active nucleus or a possible galactic wind would accelerate the flushing by new gas, while enrichment by evolving massive stars will moderate the local metal depletion.

5. SUMMARY

Close association of a chain of H II regions with the molecular bar in the center of NGC 6946 indicates that massive star formation is enhanced by cloud coalescence or collisions; tidal disruption of clouds which could quench star formation in galaxies with a strong bar has a minimal influence in NGC 6946 probably because of the weak bar potential. Line ratios used as abundance indicators, such as [O III]/H\alpha and [N II]/[O II], show anomalous behavior in the center of the galaxy; the mean radial trends of these line ratios are consistent with a flat abundance gradient for \( 0 \lesssim R \lesssim 0.4 R_{eff} = 2.5 \) kpc. Although strong fluctuations of line ratios involving the ion O \( ^{14 +} \) are expected in high-metallicity gas, the behavior of abundance ratios indicates some dilution of the gas in the inner regions of the galaxy by lower metallicity gas brought in by radial inflow along the bar. Estimates of star formation rate show that the gas may not be consumed as fast as it flows into the inner regions. NGC 6946 provides so far the best case that the presence of the bar may affect the distribution of elements in a galaxy, at least in the central regions. Beyond the radial range of the bar, the abundance gradient appears normal, as also demonstrated by Martin & Roy (1992) for another barred spiral galaxy, NGC 4303.

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