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ABUNDANCES IN SPIRAL GALAXIES: SPATIAL PROFILES AND GLOBAL CORRELATIONS

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RESUMEN

He revisado algunos de los avances más recientes sobre la medición de abundancias en galaxias espirales, poniendo énfasis en la magnitud de las variaciones de abundancias locales y en las correlaciones de abundancias y gradientes de abundancias, con las propiedades de la estructura galáctica. Las determinaciones recientes de la relación edad-metalicidad para estrellas enanas F-G de la vecindad solar sugieren una gran variación intrínseca en metalicidad a una cierta edad, en desacuerdo con la estimación de la dispersión intrínseca en regiones H II de galaxias espirales. Al examinar los datos estelares, estos revelan una dependencia de distancia en la dispersión de abundancias, sugiriendo errores sistemáticos inesperados. La pendiente de los gradientes de abundancias por unidad de escala, no muestran correlación alguna con la luminosidad de la galaxia; muestran una dispersión consistente en su totalidad con errores observacionales, sugiriendo una evolución homóloga con respecto a la composición. Hay evidencia de que la abundancia de oxígeno en un valor dado del brillo superficial está correlacionada con la luminosidad de la galaxia en el sentido de que las galaxias más luminosas tienen mayor O/H, a misma μ.

ABSTRACT

I review some of the most recent developments regarding abundance measurements in spiral galaxies, with emphasis on the magnitude of local abundance variations and on the correlations of abundances and abundance gradients with galaxy structural properties. Recent determinations of the age-metallicity relation for solar neighborhood F-G dwarf stars suggest a large intrinsic variation in metallicity at a given age, in disagreement with estimates of the intrinsic dispersion in spiral galaxy H II regions. Closer examination of the stellar data reveal a distance dependence in the abundance scatter, suggesting unsuspected systematic errors. The slope of abundance gradients per unit scale length show no correlation with galaxy luminosity, with a scatter consistent with being entirely due to observational errors, suggesting homologous evolution with regard to composition. There is evidence that the oxygen abundance at a fixed value of surface brightness correlates with galaxy luminosity in the sense that the more luminous galaxies have higher O/H at the same μ.

Key words: **GALAXIES: ABUNDANCES — GALAXIES: SPIRAL — H II REGIONS**

1. OVERVIEW AND BRIEF REVIEW

One of the goals of the study of abundances and composition gradients in spiral galaxies (and here I mean primarily from spectrophotometry of H II regions), is to pull out clues that will constrain the star formation histories, evolution of the gas, and perhaps even the formation of disk galaxies. This is by nature an indirect task, since interstellar abundances represent the cumulative star formation and gas dynamical histories of a galaxy, and so we must rely on comparing interstellar abundances and abundance gradients with galaxy structural properties to see if interesting correlations fall out. This has suffered in the past because of limited samples of data points and erratic spatial sampling within a given galaxy, but now larger, deeper data samples with adequate radial coverage are being accumulated so that gradients can be accurately defined. In addition, improved photometry and neutral gas data for spirals are also accumulating.

Spectroscopy study of a sufficient number of H II regions in spiral galaxies, typically reveals a strong radial gradient in metallicity, as determined from O/H (Figure 1). At TexMex IV, Kennicutt (Kennicutt et al. 1993) reviewed the status of abundances studies in spirals based on data acquired from the large-scale studies of Zaritsky, Kennicutt, & Huchra (1994; ZKH) and Vila-Costas & Edmunds (1992; VCE). The ZKH study

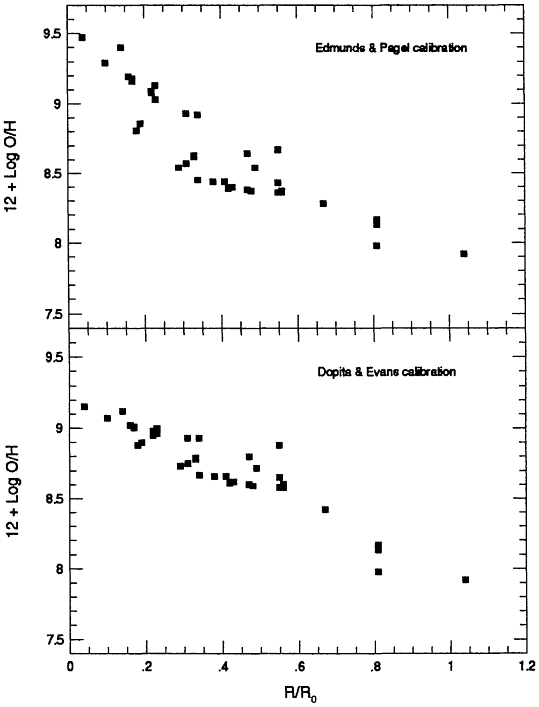

Fig. 1. The abundance gradient in M101 (Kennicutt & Garnett 1996), based on two different calibrations for O/H vs. oxygen line strength.

showed an apparent wide spread in the strength of abundance gradients in spirals, with little correlation with Hubble type; they confirmed that the metallicity at some fiducial radius within a spiral correlates with galaxy luminosity, as noted by Garnett & Shields (1987), and also correlates with the maximum circular velocity V_c, a more physical measure of galaxy mass. A surprisingly tight correlation of O/H with galaxy surface brightness seems to exist for late-type spirals (Edmunds & Pagel 1984, VCE); however, this seems to break down for earlier Hubble types (Sab/Sb/Sbc). The significance of this is uncertain at present.

In this review I shall concentrate on three problems for which new observational results have appeared: (1) the magnitude of small-scale spatial inhomogeneities in metallicity in spirals; (2) large-scale abundance variations and possible environmental effects; and (3) the metallicity - surface brightness relationship and correlations with galaxy structural properties. I will concentrate on non-barred spirals; barred spirals generally seem to have shallow gradients resulting from the strong dynamical influence of the bar (Martin & Roy 1994), and so may evolve in a significantly different manner. I will also not discuss low surface brightness spirals here, although they may provide very important clues to understanding the chemical evolution of spirals; there is insufficient data on abundances in LSB spirals to infer much about their evolution or to compare with normal spirals.

2. ARE SPIRALS WELL-MIXED IN ABUNDANCE?

The question of whether galaxies are well-mixed in abundance on various scales has been with us for some ten years. An early manifestation was the discrepancy between measured abundances in the Orion Nebula and solar neighborhood F and G dwarfs (see Peimbert 1993); this has since grown to a discrepancy between young population objects in general (B stars, H II regions, diffuse atomic gas) and the low mass disk stars. More recently, a splendid study of abundances in local F and G disk stars by Edvardsson et al. (1993) turned up more apparent evidence for large abundance variations: their age-metallicity diagram for the stars showed very large scatter at a given age (±0.4–0.5 dex), which exceeded the estimated uncertainties.

A wide variety of models have been invoked to explain these apparent discrepancies, of which I name just

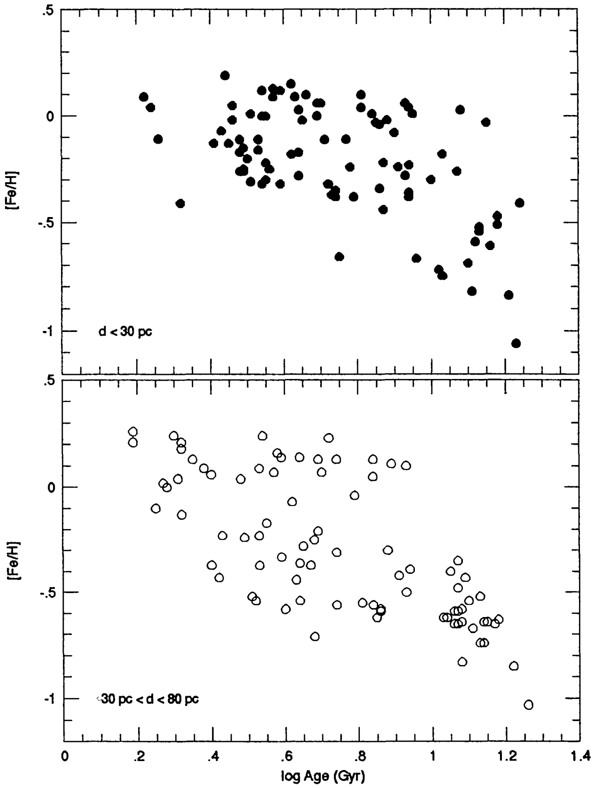

Fig. 2. Distance dependence of the scatter in the age-metallicity relation for solar neighborhood stars, based on data from Edvardsson et al. 1993. The upper panel shows stars closer than 30 pc, the lower panel stars more distant than 30 pc. The scatter in [Fe/H] is almost twice as large for the more distant stars.

a few: (1) errors in nebular abundances, e.g., because of electron temperature fluctuations (Peimbert 1967); (2) local infall of metal-poor gas (Meyer et al. 1994); (3) radial diffusion of stellar orbits (François & Matteucci 1993; Wielen, Fuchs, & Dettbarn 1996); (4) inhomogeneous chemical evolution/stochastic processes (van den Hoek & de Jong 1997; Copi 1997); and others (inefficient mixing, grains, etc.).

Nevertheless, the measured scatter in the age-metallicity relation disagrees significantly with that inferred from the H II region data for M101 from Kennicutt & Garnett (1996), which they found to be intrinsically rather small, less than ±0.2 dex (see Fig. 1). Thus, it would seem appropriate to ask how much of the scatter in the stellar age-metallicity diagram is real. A potential source of considerable uncertainty is the ages of the stars, which are derived from placing the star in the H-R diagram. This requires an accurate parallax measurement. Since the Edvardsson et al. sample extends to stars as far away as 80 pc, distances (and thus luminosities) to many of the stars may have significant uncertainty.

A simple test is to see if there is a distance dependence in the age-metallicity relation. An illustration of this is shown in Figure 2, in which we have simply divided the Edvardsson et al. sample into two groups, one with stars closer than 30 pc, and the other with stars farther than 30 pc (Garnett & Kobulnicky 1998). The result is striking: the more distant sample has shows a much larger scatter in the age-metallicity relation than the nearby sample. In fact, nearly all the scatter in the Edvardsson et al. age-metallicity relation can be accounted for by the more distant stars. This simple analysis indicates that there is a distance-dependent error creeping into the age-metallicity analysis; at the present time it is not certain what the cause is. A reanalysis of the stellar data with parallaxes from HIPPARCOS should clarify the situation.

If one considers only the sample with the nearest dwarf stars, one infers a scatter of only about ± 0.2 dex in the age-metallicity relation. This is consistent with the scatter being due almost entirely to observational errors, and is in reasonable accord with the scatter in O/H observed in M101 (Kennicutt & Garnett 1996).

Although it is likely that there is some small-scale intrinsic scatter in abundances (from stochastic effects), I conclude that such intrinsic variations must be smaller than about 0.2 dex.

3. LARGE-SCALE ABUNDANCE VARIATIONS AND ENVIRONMENTAL EFFECTS

One might expect the environment of a spiral galaxy to have an influence on composition and the shape of abundance gradients. In the dense environment of clusters, for example, a hot intracluster medium can remove gas from galaxies through ram pressure and viscous stripping, and may hinder cosmological infall of metal-poor gas. Evidence for such effects may be found in the work of Skillman, Kennicutt, & Shields (1996) on Virgo Cluster spirals; they find that those spirals with the largest H I deficiencies appear to have systematically higher abundances than similar field spirals. The samples of cluster and field spirals are relatively small; however, so the results are not yet statistically significant. Further study of spirals in other clusters will help to put the results on a firmer foundation.

Companion or satellite galaxies may affect the observed distribution of abundances in a disk galaxy. Companions can exert tidal forces which may distort the shape of a galaxy or induce star formation. Gas-rich, metal-poor satellites may be accreted onto a more massive spiral and dilute the composition of the interstellar gas. For example, Zaritsky (1995) has suggested that accretion of a gas-rich dwarf irregular may steepen the composition gradient of a spiral. Since the cross-section for accreting a dwarf companion is greater for the outer disk, the metal-poor gas from the dwarf would dilute the outer disk and steepen any abundance gradient; accretion of the gas may trigger new star formation as well. Thus, Zaritsky predicts that the slope of the abundance gradient should correlate with the difference in the spiral's B-magnitude from the mean Tully-Fisher relation. There is an interesting hint of such a correlation for the few spirals with Cepheid-based distances, but the uncertainties at present are rather large.

A more direct way to detect the influence of dwarf companion is to look for evidence of large-scale deviations from a smooth composition gradient within a spiral. Possible evidence for such an effect can be found in M101 (Kennicutt & Garnett 1996). Kennicutt & Garnett noted an asymmetry in the apparent abundances between the NW and SE halves of M101, such that the SE half has lower apparent abundances. Examination of various diagnostic line ratios indicated that the asymmetry was unlikely to be due to differences in the ionizing stars or nebular excitation. The abundance deviation in the SE coincides with an obvious distortion of the spiral arms in that region, and also with the projected position of ridge of high-velocity H I gas (van der Hulst & Sancisi 1988). It is unclear yet whether the abundance asymmetry is due to accretion of metal-poor gas or simply the result of a distortion or warping of the galaxy in the SE. Nevertheless, this study demonstrates the new realms of investigation that may be explored using spectroscopy of large samples of H II region in spirals.

4. GLOBAL CORRELATIONS; METALLICITY VS. SURFACE BRIGHTNESS

The abundances derived for a galaxy must ultimately be compared with the galaxy's photometric properties and gas content, for it is the conversion of gas to stars that determines the metallicity within a galaxy. Various investigators have attempted to find correlations between metallicity and galaxy properties to understand the origin and evolution of galaxies in the context of the Hubble sequence.

VCE and ZKH have compiled a large amount of new and published data on abundances in galaxies to look at how composition and composition gradients vary with galaxy properties. One of the more striking correlations is the relation between metallicity and galaxy luminosity or maximum rotational velocity, alluded to in the introduction. ZKH noted the remarkable uniformity of this correlation over 11 magnitudes in galaxy luminosity, which suggests a common mechanism regulating the global metallicity of each galaxy. The mechanism is not very well understood at present, although metal-enhanced mass loss is commonly invoked.

Another commonly-recognized correlation is illustrated in the top panel of Figure 3: the steepness of abundance gradients (when expressed as dex/kpc) decreases with galaxy luminosity. This is often summed up as "luminous galaxies have shallower gradients" or "early-type spirals have shallow gradients". However, it is not clear that the gradient per unit kpc is physically meaningful. More luminous galaxies tend to have larger disk scale lengths, and so if one looks at the gradient per disk scale length, as in the bottom panel of Fig. 3, the correlation goes away. Caution is thus called for in interpreting the slope of a gradient in units of physical length. Curiously, if one considers the errors in the computed gradients (25% is a typical uncertainty), then the intrinsic scatter in measured gradient slopes seems to be remarkably small. This may be telling us that spirals follow a homology relation with regard to chemical evolution. It would be interesting to see how small the intrinsic dispersion in abundance gradients can be.

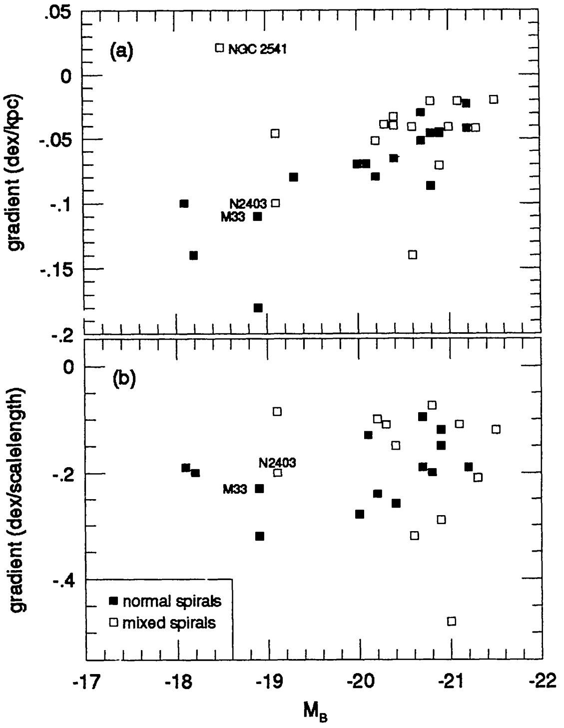

Fig. 3. The correlation of abundance gradient vs. galaxy luminosity, from Garnett et al. (1997). The upper panel shows abundance gradients per kpc, while the lower panel shows gradients per unit disk scale length.

The uniformity of abundance gradients as a function of scale length suggests a close correlation between metallicity and disk surface brightness. Indeed, McCall (1982) and Edmunds & Pagel (1984) noted a remarkably tight correlation between O/H and disk surface brightness for late-type spirals. Although any model which produces an exponential disk and an abundance gradient will yield such a correlation, it is not clear that it should be a tight one. This has provided part of the motivation for models of self-regulated star formation, in which the radiation and mechanical energy produced by stars feeds back into the surrounding ISM and acts to inhibit further star formation. Models of this kind have been explored by Phillips & Edmunds (1991) and Ryder (1995), and appear to do a good job of reproducing the correlations of both star formation rate and O/H with surface brightness. On a cautionary note, however, the interaction of the stellar energy output with the ISM is still poorly understood.

It should also be noted that early-type spirals do not follow the same O/H-surface brightness correlation as the late types (Edmunds & Pagel 1984). This has recently been put on a more quantitative basis by Garnett et al. (1997). Figure 4 displays the characteristic metallicity at two fixed values of disk surface brightness for a sample of spirals having either *I*- or *R*-band surface photometry. The figure shows that there is a remarkable correlation between the metallicity at a given surface brightness and the luminosity of a galaxy. There is also a hint that earlier Hubble types are the ones with the higher abundances, although there is insufficient data to be conclusive. I believe this may be an important clue to the origin of the differences in composition between galaxies. Possible explanations include a greater amount of prompt initial enrichment for the more luminous spirals (this might be signaled by a strong correlation with Hubble type), or perhaps systematic variations in infall rates. A larger sample of data is need to put the correlation on a firmer footing.

5. SUMMARY

New studies of composition gradients in spiral galaxies are revealing a number of interesting correlations between abundances and galaxy properties to challenge the galaxy modelers. One of the challenges for observers in the future is to compile a truly homogeneous set of abundance data for spirals. Some of the immediate needs

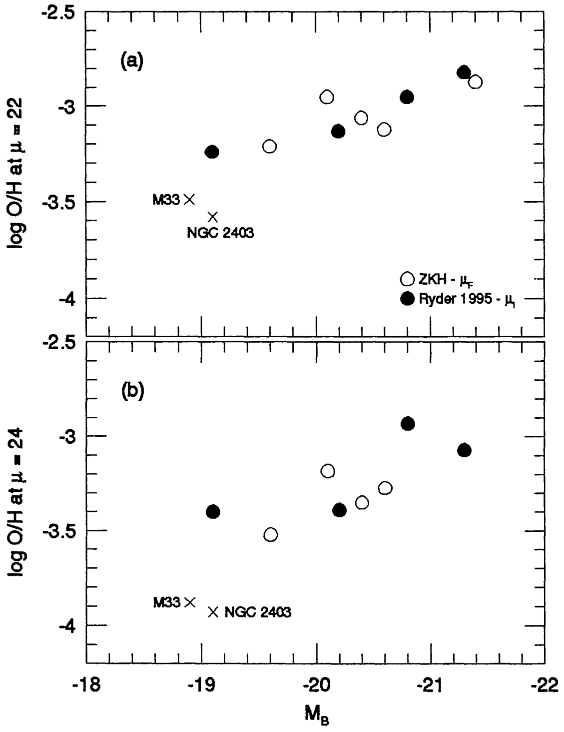

Fig. 4. Abundance at fixed value of galaxy surface brightness vs. galaxy luminosity. More luminous spirals appear to have higher abundances at a fixed surface brightness.

I see are: (1) extension of the data set to include missing Hubble types. In particular, there is a serious lack of information on gradients for very early Hubble types (Sa-Sab), and curiously enough, very late types (T = 7–8). These are needed to provide a longer baseline for understanding abundance properties as a function of Hubble type. (2) Surface photometry of spirals, preferably in the infrared or near-infrared, which better sample the stellar mass density. (3) Larger samples of H II region data points per galaxy. This will reveal regions of anomalous composition as in M101. The O/H gradient in M101 is, in fact, different in the NW and SE halves of the galaxy, due to the galaxy's distortion. This was only revealed through having a sample of 40 regions with high-quality spectroscopy. (4) A conscious effort to study galaxies having both surface photometry and H I/rotation curve data. Such data exists for quite a few galaxies now; unfortunately, those galaxies are very often not the ones we have been measuring abundances in! If the mountain refuses to come to us, then we must seek out the mountain ourselves...

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