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Chemical abundances in the polar disk of NGC4650A: implications for cold accretion scenario

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Abstract. We used high resolution spectra in the optical and near-infrared wavelength range to study the abundance ratios and metallicities of the HII regions associated with the polar disk in NGC4650A, in order to put constraints on the formation of the polar disk through cold gas accretion along a filament; this might be the most realistic way by which galaxies get their gas. We have compared the measured metallicities for the polar structure in NGC4650A with those of different morphological types and we have found that they are similar to those of late-type galaxies: such results are consistent with a polar disk formed by accretion from cosmic web filaments of external cold gas.

Key words. galaxies: individual, NGC4650A - galaxies: formation and evolution - galaxies: interactions - galaxies: peculiar - galaxies: abundance

1. Introduction

The Cold Dark Matter scenario for galaxy formation is based on hierarchical mass assembly (Cole et al. 2000), which predicts that the observed galaxies and their dark halo (DH) were formed through repeated merging processes of small systems (De Lucia et al. 2006, Genel et al. 2008).

The gas fraction is a key parameter in the physics of gravitational interactions. Galaxies can get their gas through several interacting processes, such as smooth accretion, stripping and accretion of primordial gas, which are equally important in the growth of galaxies; recent theoretical works have explained the build-up of high redshift disk galaxies by the accretion of external gas from the cosmic web filaments, which turns to be the most realistic way by which galaxies get their gas (Kereš et al. 2005, Keres 2008, Brosch et al. 2010, Dekel et al. 2009, Bournaud & Elmegreen 2009).

Recently, Macciò et al. (2006) and Brook et al. (2008) have studied the formation and evolution of a polar disk galaxy: a long-lived polar structure will form through cold gas accretion along a filament, extended for ∼ 1 Mpc, into the virialized dark matter halo. In this scenario there is no limits to the mass of the accreted material, thus a very massive polar disk may develop either around a stellar disk or a spheroid. The morphology and kinematics of one simulated object are quite simi-

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lar to those observed for the polar disk galaxy NGC4650A. This galaxy is the prototype for PRGs; the polar disk is very massive, since the total HI mass in this component is about $10^{10} M_\odot$, which added to the mass of stars is comparable with the total mass in the central spheroid.

Recent theoretical works have argued that the accretion of external cold gas from cosmic web filaments might be the most realistic scenario for this polar disk. In fact, if the polar structure forms by accretion from cosmic web filaments of external cold gas, we expect lower metallicity with respect to those of same luminosity spiral disks, with values of $Z \sim 1/10 Z_\odot$.

2. Chemical abundance determination

2.1. Empirical methods

We derived the *Oxygen abundance parameter* $R_{23} = ([OII]\lambda3727 + [OIII]\lambda\lambda4959 + 5007)/H_\beta$ (Pagel et al. 1979), and the *Sulphur abundance parameter* $S_{23} = ([SII]\lambda\lambda6717 + 6731 + [SIII]\lambda\lambda9069 + 9532)/H_\beta$ (Díaz & Pérez-Montero 2000). We need to use both indicators to break the degeneracy with the metallicity that affect R_{23}; we calibrate the oxygen abundance through the Sulphur abundance parameter by using the relation $12 + log(O/H) = 1.53 log S_{23} + 8.27$, introduced by Díaz & Pérez-Montero (2000).

We also used another empirical method introduced by Pilyugin (2001), that propose to use the excitation parameter $P = R_3/R_{23}$ (where $R_3 = ([OIII]\lambda\lambda4929 + 5007)/H_\beta$), to estimate the oxygen abundance as a function of P and R_{23}. This method, called "P-method", propose to use a more general relation of the type $O/H = f(P, R_{23})$, compared with the relation $O/H = f(R_{23})$ used in the R_{23} method. The equation related to this method is the following

$$12 + log(O/H)_P = \frac{R_{23} + 54.2 + 59.45P + 7.31P^2}{6.07 + 6.71P + 0.371P^2 + 0.243R_{23}}$$

It can be used for oxygen abundance determination in moderately high-metallicity HII regions with undetectable or weak temperature-sensitive line ratios (Pilyugin 2001).

The abundances derived with both methods are consistent and we also find an absence of any metallicity gradient along the polar structure.

2.2. Direct methods

We derived the oxygen abundance of the polar disk directly by the estimate of the O^{++} and O^{+} ions electron temperature. According to Izotov et al. (2005) and Pilyugin et al. (2006), $12 + log(OIII/H) = f(OIII[4959 + 5007]/H_\beta, t_3)$ and $12 + log(OII/H) = f(OII[3727]/H_\beta, t_2, Ne)$, where t_3, t_2 are the electron temperatures within the OIII and OII zones respectively, and Ne is the electron density. The total oxygen abundance is O/H=OIII/H+OII/H and is in good agreement with the values derived with empirical methods. By solving the equations of the statistical equilibrium within the five- level atom approximation, both t_3 and t_2 are function of Ne and of the line ratios OIII[4959+5007]/[4363] and OII[3723]/[7325] respectively. For NGC4650A, Ne was estimated by the line ratio SII[6717]/[6731].

3. Results

In order to test the cold accretion scenario for the formation of polar disk galaxy NGC4650A, we estimated the oxygen abundance $12 + log(O/H)$ along the polar disk, by using both the empirical and direct methods.

By comparing the abundance of the polar disk with those of galaxies of different morphological type, but same luminosity, we find that NGC4650A has metallicity lower than spiral galaxy disks of the same total luminosity (Fig.1).

The average metallicity for the polar disk of NGC4650A is $Z = 0.2\ Z_\odot$ and compared with the typical values for spiral galaxies, turns to be lower. This value is consistent with those predicted for the formation of disks by cold accretion processes (Agertz et al. 2009).

Moreover, the oxygen abundance along the polar disk of NGC4650A is constant (Fig. 2):

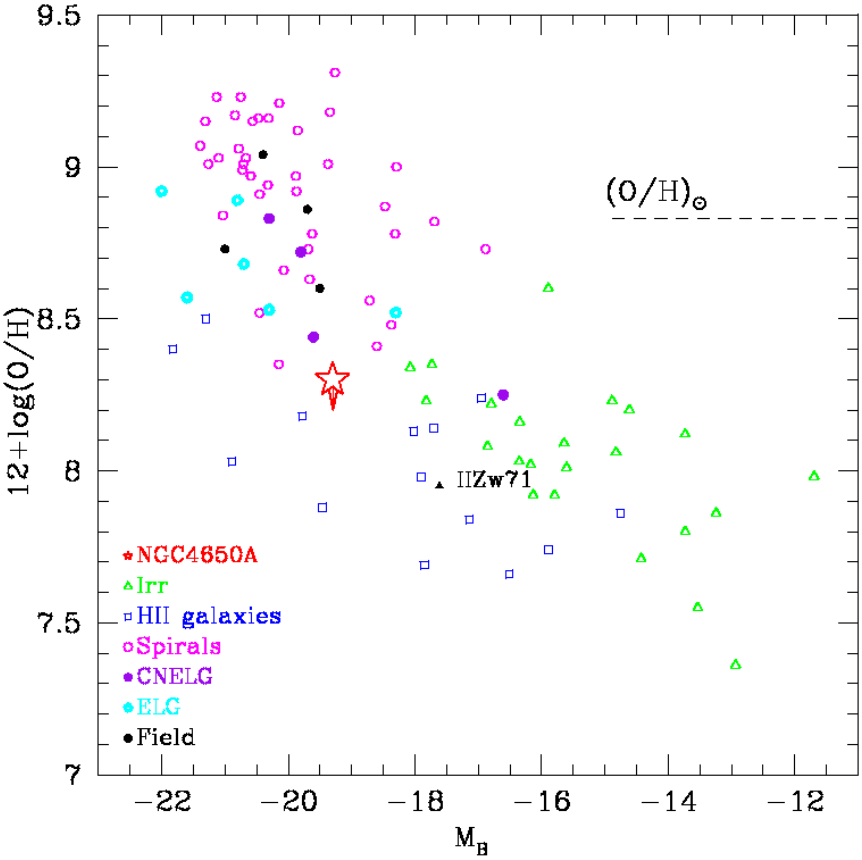

Fig. 1. Oxygen abundance vs absolute blue magnitude for CNELGs (purple filled circles), ELGs (cyan open circles), four field galaxies with emission lines (filled black circles), nearby dwarf irregulars (open triangles), local spiral galaxies (open circles), local HII galaxies (open squares), NGC4650A (star) and the polar disk galaxy IIZw71 (Perez-Montero et al. 2009), the dashed line indicates the solar oxygen abundance. The arrow indicates the shift of the value of the oxygen abundance if we use the direct methods to evaluate it. The total B-band magnitude for NGC4650A ($M_B = -19.3$) has been evaluated by using the same value of H_0 used by Kobulnicky & Zaritsky (1999) in order to compare NGC4650A with galaxies in their sample.

this suggests that the metal enrichment is not influenced by the stellar evolution of the central spheroid where the last burst of star formation occurred between 3 to 5 Gyrs ago (Iodice et al. 2002): this turns also to be consistent with a later formation of the polar disk. The absence of any metallicity gradient is also found in some other PRGs (Brosch et al. 2010), while a strong gradient is observed in spiral galaxies. These observed features in spiral disks are well explained by the infall models of galaxy formation which predict that they build up via accretion by growing inside-out (Matteucci & Francois 1989; Boissier & Prantzos 1999) and such process generates the observed gradients, while the absence of gradient in NGC4650A turns to be consistent with infall of metal-poor gas from outside which is still forming the disk.

Taking into account that the polar disk is very young, since the last burst of star formation occurred less than 1 Gyr ago (Iodice et al.

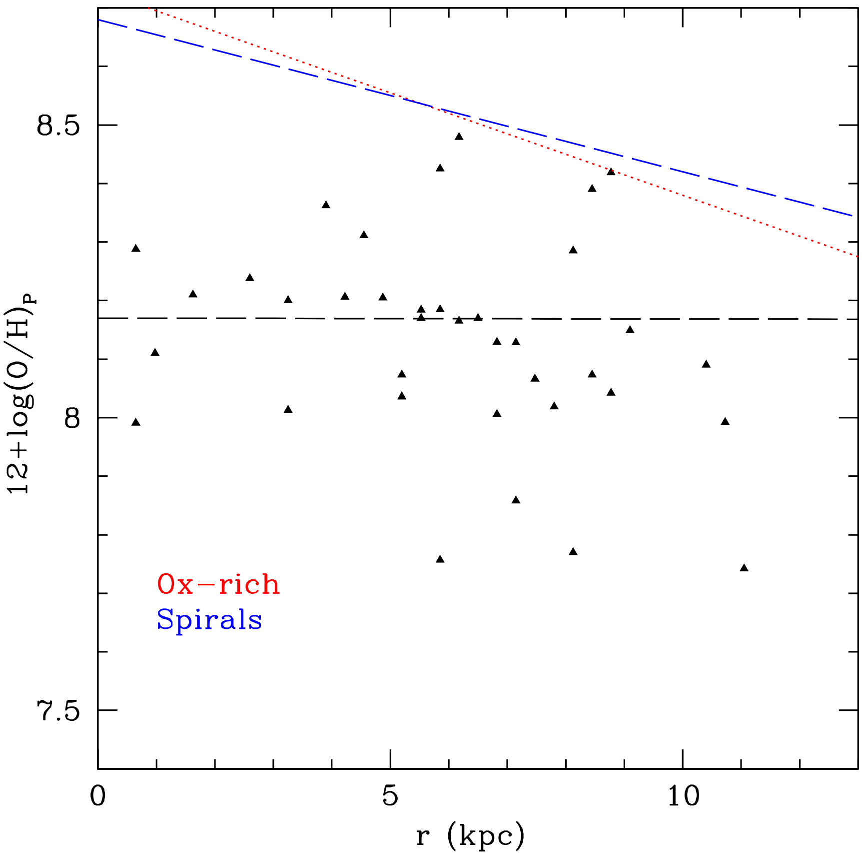

Fig. 2. Oxygen abundance derived with empirical methods proposed by Pilyugin (2001) versus radius. The superimposed lines are the linear best fit derived by Pilyugin et al. (2006); the red line represents the best fit to the abundance of oxygen-rich spirals, while the blue line is that related to ordinary spirals. The black line is the best fit obtained for NGC4650A.

2002), we check if the present SFR of 0.06 $M_{\odot}/yr$, and even 2 and 3 times higher (i.e. $SFR = 0.12 M_{\odot}/yr$ and $SFR = 0.18 M_{\odot}/yr$), can give the estimated metallicity of $Z = 0.2\ Z_{\odot}$ and how strongly could increase the metallicity with time.

We used a linearly declining SFR (Bruzual & Charlot 2003) $\psi(t) = 2M_{\star}\tau^{-1}[1 - (t/\tau)]$ (typically used for late-type galaxies), to estimate the expected stellar mass for the three different values of the SFR (0.06, 0.12 and 0.18 $M_{\odot}/yr$) and three epochs (0.8 Gyr, 1 Gyr and 2 Gyrs), obtaining stellar masses in the range $4 \times 10^{9} M_{\odot} \leq M_{\star} \leq 1 \times 10^{10} M_{\odot}$. The stellar mass ($M_{\star} \sim 4 \times 10^{9} M_{\odot}$) in the disk from NIR observations (Iodice et al. 2002) falls within this range. Than, by using the mass-metallicity relation derived by Tremonti et al. (2004), where $12 + log(O/H) = -1.492 + 1.847 log(M_{\star}) - 0.08026 (log M_{\star})^{2}$, we found that $1.02\ Z_{\odot} \leq Z \leq 1.4\ Z_{\odot}$. This shows that the present SFR for the polar disk ($SFR = 0.06\ M_{\odot} yr^{-1}$) is able to increase the metallicity of about $0.2\ Z_{\odot}$ after 1 Gyr. The derived values for Z are larger than $Z = (0.2 \pm 0.002)\ Z_{\odot}$, found by using the element abundances: this differences could be attributed to the accretion of metal-poor gas.

Given all the evidences shown above, we can infer that the cold accretion of gas by cosmic web filaments could well account for both the low metallicity, the lack of gradient and the high HI content in NGC4650A. An independent evidence which seems to support such scenario for the formation of polar disks comes from the discovery and study of an isolated polar disk galaxy, located in a wall between two voids (Stanonik et al. 2009): the large HI mass (at least comparable to the stellar mass of the central galaxy) and the general underdensity of the environment can be consistent with the cold flow accretion of gas as possible formation mechanism for this object.

The present work remarks how the use of the chemical analysis can give strong constraints on the galaxy formation, in particular, it has revealed an independent check of the cold accretion scenario for the formation of polar disk galaxies. This study also confirmed that this class of objects needs to be treated differently from the polar ring galaxies, where the polar structure is more metal rich and a tidal accretion or a major merging process can reliably explain the observed properties (Bournaud & Combes 2003). Finally, given the similarities between polar disks and late-type disk galaxies, except for the different plane with respect to the central spheroid, the two classes of systems could share similar formation processes. Therefore, the study of polar disk galaxies assumes an important role in the wide framework of disk formation and evolution, in particular, for what concern the "rebuilding" of disks through accretion of gas from cosmic filaments, as predicted by hierarchical models of galaxy formation (Steinmetz Navarro 2002).

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