

# Molecular content of polar-ring galaxies<sup>★,★★</sup>

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## ABSTRACT

We have searched for CO lines in a sample of 21 new morphologically determined polar-ring galaxies (of which nine are kinematically confirmed), obtained from a wide search in the Galaxy Zoo project by Moiseev and collaborators. Polar-ring galaxies (PRGs) are a unique class of objects, tracing special episodes in the galaxy mass assembly: they can be formed through galaxy interaction and merging, but also through accretion from cosmic filaments. Furthermore, they enable the study of dark matter haloes in three dimensions. The polar ring itself is a sub-system rich in gas, where molecular gas is expected, and new stars are formed. Among the sample of 21 PRGs, we have detected five CO-rich systems, that can now be followed up with higher spatial resolution. Their average molecular mass is  $9.4 \times 10^9 M_{\odot}$ , and their average gas fraction is 27% of their baryonic mass, with a range from 15 to 43%, implying that they have just accreted a large amount of gas. The position of the detected objects in the velocity-magnitude diagram is offset from the Tully-Fisher relation of normal spirals, as was already found for PRGs. This work is part of our multi-wavelength project to determine the detailed morphology and dynamics of PRGs, test through numerical models their formation scenario, and deduce their dark matter content and 3D-shape.

**Key words.** galaxies: evolution – galaxies: general – galaxies: halos – galaxies: ISM – radio lines: galaxies

## 1. Introduction

Polar-ring galaxies (PRGs, see Fig. 1) are peculiar objects composed of a central component (usually an early-type galaxy) surrounded by an outer ring or disk, made up of gas, stars, and dust, which orbits nearly perpendicular to the plane of the gas-poor central galaxy (Whitmore et al. 1990). For some well-known systems studied with high spatial resolution, it was possible to show that the polar system is in fact a polar disk, more than a polar ring (e.g. Iodice et al. 2002c). However, polar disks and rings are both gathered into the same PRG class.

Measurements of their kinematics can therefore give some insight in the 3D-shape of their dark matter, which can be generalised to the progenitor spiral galaxies, provided that their formation mechanism is known.

We note that many of the best cases of PRGs have a relatively massive polar component that cannot be treated as simple test particles, but self-gravity must be taken into account.

### 1.1. Formation scenarios for polar-ring galaxies

From dynamical arguments, the two misaligned systems cannot be formed simultaneously, as confirmed by the younger ages of the polar rings/disks (Iodice et al. 2002a,b,c), and the fact that

most of the gas of the system is in the polar disk (van Driel et al. 2000, 2002). At least three formation mechanisms have been discussed in the literature, the first two involving galaxy interactions:

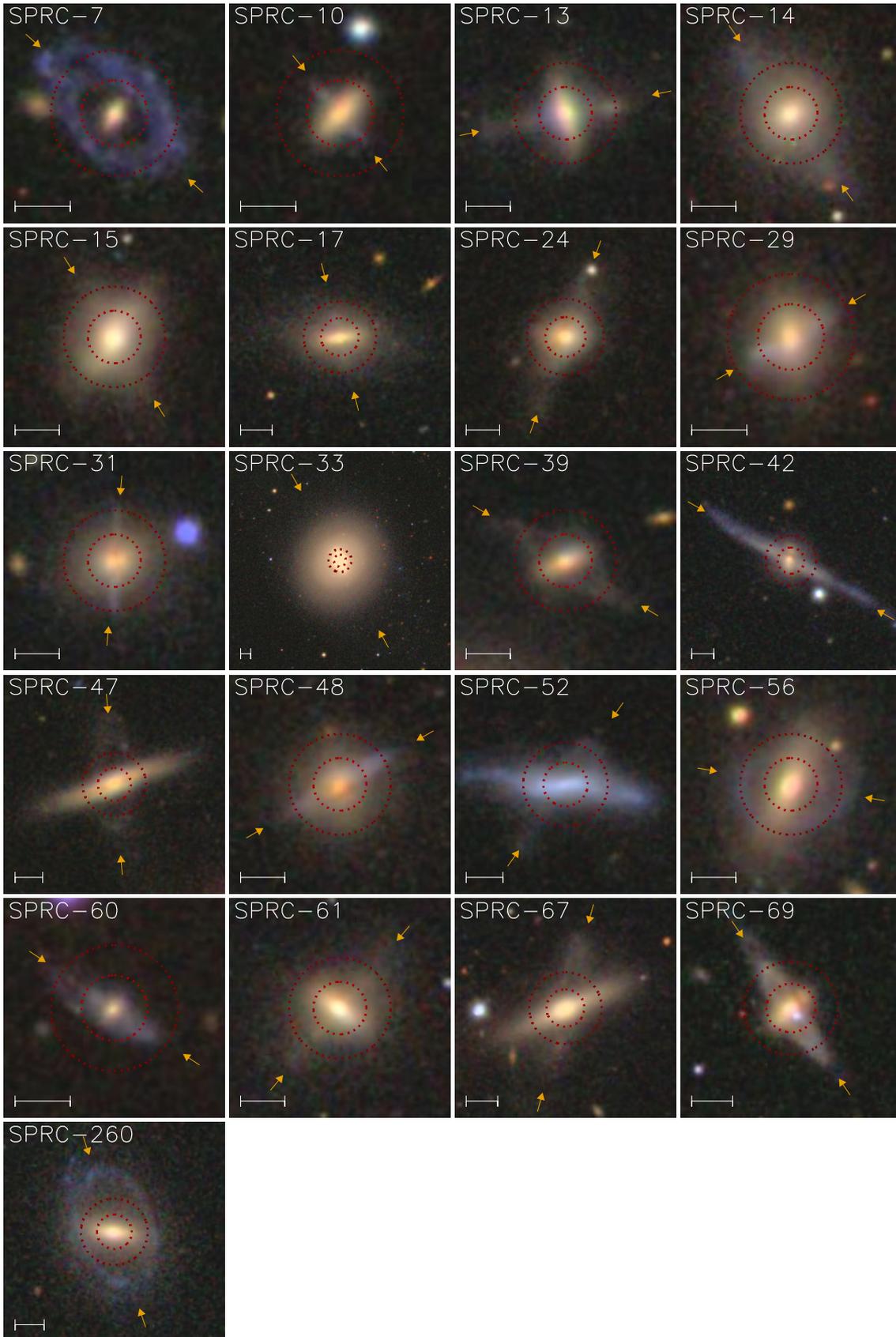
- 1) the accretion scenario, where two interacting galaxies exchange mass, as invoked by Schweizer et al. (1983) and simulated by Reshetnikov & Sotnikova (1997);
- 2) the merging scenario, or the head-on collision of two orthogonal spiral galaxies, first studied by Bekki (1997, 1998). Bournaud & Combes (2003) have shown through simulations that statistically the first scenario is more frequent, and more likely to represent observations;
- 3) the cosmic formation scenario, where the PRGs form through the misaligned accretion of gas from cosmic filaments (Maccio et al. 2006; Brook et al. 2008). The gas of the PR is then of lower metallicity than in the first scenarios.

The fact that some PRGs are polar disks more than polar rings supports the formation through cosmic accretion, as shown by Spavone et al. (2010). Also, the low metallicity, and flat abundance gradients could favour this mechanism (Spavone et al. 2011), while the presence of a true ring supports the tidal accretion.

Snaith et al. (2012) have developed in more detail the formation scenario proposed by Brook et al. (2008). In their simulations, the polar disk is progressively formed out of gas and dark matter infalling from a cosmic filament, after the last major merger has re-oriented the old system in a perpendicular direction (and formed the host). This implies that the dark matter is aligned with the polar system.

\* Based on observations carried out with the IRAM 30 m telescope. IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).

\*\* Spectra of detections are available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](http://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/554/A11>



**Fig. 1.** SDSS DR8 colour images of the polar ring sample (see Table 1). The scale bar in each image is 10 arcsec long, and the two dashed circles indicate the full width at half power (FWHM) beam width for the CO(1–0) and CO(2–1) observations. To identify the polar systems, we have indicated their directions with arrows, corresponding to the PA displayed in Table 1. SPRC-33 contains a giant HI polar disk with very weak stellar counterpart detected in UV images only (Bettoni et al. 2010; Moiseev et al. 2011).

## 1.2. The dark matter issue

The 3D-shape of dark matter halos has been estimated in many objects (e.g. Combes 2002), and has recently been investigated through edge-on galaxies, allowing us to study the gas flaring of the disk (e.g. O’Brien et al. 2010; Peters et al. 2013), through gravitational lensing (van Uitert et al. 2012), or through satellite disruption (Law et al. 2009). There is a large scatter in the flattening derived, i.e. an axis ratio between 0.2 and 1. PRGs are privileged systems for this study. Since the ring is gas rich and rotates around the pole, it is a probe of the gravitational potential in the third dimension, which is normally inaccessible in normal spirals. It is therefore a unique tool for determining the 3D-shape and consequently constraining the nature of dark matter. From the shape of dark haloes in PRGs, we should be able to deduce the shape of dark haloes in normal galaxies, knowing the formation mechanisms of PRGs.

In all previous studies (e.g. Whitmore et al. 1987; Sackett & Sparke 1990; Sackett et al. 1994; Reshetnikov & Combes 1994; Combes & Arnaboldi 1996; Iodice et al. 2003) the common conclusion is that PRGs are indeed embedded in a dark halo. However, the solutions for the 3D-shape differ, according to models and accuracy of data: the dark halo is almost spherical for Whitmore et al. (1987), flattened along the equatorial plane of the host galaxy (Sackett et al. 1994), or flattened along the polar-ring plane (Combes & Arnaboldi 1996). This last solution is supported for a large number of PRGs by Iodice et al. (2003), through a study of the Tully-Fisher (TF) diagram for PRGs.

The position of the PRGs in the TF diagram is very peculiar, and does not fit the sequence of normal disk galaxies (Iodice et al. 2003; Reshetnikov 2004). The rotational velocity is obtained through HI-21cm measurement from the gas in the edge-on polar disks. Most of the PRGs have higher than normal rotational velocities, for their luminosities. This is not expected if the dark halo is spherical or flattened to the equatorial plane of the host, because then the observed velocity corresponds to the apocenter of the excentric polar orbit, and is lower than the velocity observed in the equatorial plane.

Since the contrary is observed, this must be due to a flattening of the dark matter towards the polar plane. This important suggestion must be confirmed by a much larger statistics, and therefore we want to enlarge significantly the number of objects that can be considered as PRGs. Since this implies selecting objects that are more distant because the HI-21cm line is not as easy to detect at high redshift, the CO line then becomes the preferred tracer of the gas. In the present sample, our largest redshift is 0.078, but in the future with ALMA, the CO-TF will be a unique tool.

## 1.3. Molecular gas in PRGs

The molecular content of PRGs is poorly known. The first CO detection in such an object was in NGC 660 (Combes et al. 1992). Watson et al. (1994) then detected CO(2–1) in the polar rings of NGC 2685 and NGC 4650A, and later Schinnerer & Scoville (2002) made an interferometric map of the Spindle galaxy NGC 2685. Van Driel et al. (1995) found abundant CO emission in the inclined ring of NGC 660, and Crocker et al. (2008) in the center of NGC 2768. Galletta et al. (1997) observed ten PRGs in CO and found molecular masses much larger than those in early-type galaxies and also in dwarf galaxies, suggesting that PRGs cannot get their gas in a dwarf accretion only. All these are only a few cases, and more observations

are required to know better the molecular content of PRGs and to better understand their formation scenarios.

The sample is described in Sect. 2 and the observations in Sect. 3. Results are presented in Sect. 4 and discussed in Sect. 5.

## 2. The sample

Recently, Moiseev et al. (2011) have built a new catalogue of PRGs, significantly increasing the number of known candidate PRGs. The catalogue is based on the results of the original Galaxy Zoo project, where nearly a million galaxies from the Sloan Survey (SDSS) were classified. This results in the Polar Ring Catalog (SPRC) of 275 objects, in which 70 galaxies are classified as the best PRGs, and 115 as good PRG candidates. Among the 70, there are 15 kinematically confirmed PRGs. For our search, we have selected the latter, and among the best candidates, the brightest in terms of  $r$ -magnitude ( $r < 15.5$ ) (cf. Table 1).

The main goal of the present work is to obtain information on the molecular content of this sample of 21 PRGs. The global CO detection allows us to locate the object in the Tully-Fisher diagram, and to have a first information in the geometry of the dark halo. Future interferometric work on the detected PRGs will provide high resolution maps, in order to be able to compare results with numerical models.

In this article, we adopt a standard flat cosmological model, with  $\Lambda = 0.73$  and a Hubble constant of  $71 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Hinshaw et al. 2009).

## 3. Observations

The observations were carried out with the IRAM 30 m telescope at Pico Veleta, Spain, from December 2011 to January 2012. All sources were observed simultaneously in CO(1–0) and CO(2–1) lines, with the 3 mm and 1 mm receivers in parallel.

The broadband EMIR receivers were tuned in single side-band mode, with a total bandwidth of 4 GHz per polarization. This covers a velocity range of  $\sim 10400 \text{ km s}^{-1}$  at 2.6 mm and  $\sim 5200 \text{ km s}^{-1}$  at 1.3 mm. The observations were carried out in wobbler switching mode, with reference positions offset by  $2'$  in azimuth. Several backends were used in parallel, the WILMA autocorrelator with 2 MHz channel width, covering  $4 \times 4 \text{ GHz}$ , and the 4 MHz filterbanks, covering  $2 \times 4 \text{ GHz}$ .

We spent on average two hours on each galaxy, and reached a noise level between 0.6 and 1.6 mK (antenna temperature), smoothed over  $30 \text{ km s}^{-1}$  channels for all sources. Pointing measurements were carried out every two hours on continuum sources and the derived pointing accuracy was  $3''$  rms. The temperature scale is then transformed from antenna temperature  $T_A^*$  to main beam temperature  $T_{\text{mb}}$ , by multiplying by 1.17 at 3 mm and 1.46 at 1.3 mm. To convert the signals to fluxes, we use  $S/T_{\text{mb}} = 5.0 \text{ Jy/K}$  for all bands. At 2.6 mm and 1 mm, the telescope half-power beam width is  $23''$  and  $12''$  respectively. The data were reduced with the CLASS/GILDAS software, and the spectra were smoothed so that each line covers about ten channels in the plots<sup>1</sup>.

## 4. Results

### 4.1. CO detection in PRGs

Figures 2 and 3 display the CO-detected sources, in both CO lines. Two of the five detections involved kinematically

<sup>1</sup> Spectra of detections are available at the CDS.

**Table 1.** Basic data for the polar-ring galaxy sample, and sizes of the regions observed in CO(1–0) and CO(2–1).

SPRC No. <sup>a</sup>	Name	RA (2000.0)	Dec	$cz$ [km s <sup>-1</sup> ]	$g$ [mag]	$r$ [mag]	$i$ [mag]	PA [°]	Beam <sub>10</sub> [kpc]	Beam <sub>21</sub> [kpc]
7C		07 52 34.32	+29 20 49.7	18 032	17.84	16.95	16.85	48	27.9	14.0
10C		08 20 38.19	+15 36 59.8	12 736	17.16	16.29	15.79	39	19.8	9.9
13		09 14 53.66	+49 38 24.0	9521	16.10	15.37	15.06	102	14.8	7.4
14C	CGCG 121-053	09 18 15.97	+20 22 05.3	9548	15.59	14.73	14.48	35	14.8	7.4
15		09 36 34.63	+21 13 57.8	10 281	15.31	14.43	14.14	32	16.0	8.0
17		09 59 11.85	+16 28 41.5	7914	15.81	14.92	14.59	14	12.3	6.2
24		11 16 25.11	+56 50 17.0	14 133	15.85	14.98	14.63	160	21.9	11.0
29		11 53 33.56	+47 19 07.3	14 208	16.30	15.25	15.06	120	22.1	11.0
31		12 17 11.51	+31 30 37.8	14 913	16.21	15.08	14.93	175	23.1	11.6
33C	NGC 4262	12 19 30.57	+14 52 39.5	1358	12.22	11.24	10.98	29	21.1	10.6
39C		13 08 16.92	+45 22 35.2	8792	17.01	16.01	15.75	59	13.7	6.8
42	UGC 08634	13 39 04.59	+02 09 49.5	7041	15.75	15.04	14.85	60	11.0	5.5
47		13 59 41.70	+25 00 46.1	9370	15.62	14.49	14.28	5	14.6	7.3
48		14 14 20.82	+27 28 04.4	16 788	16.30	15.04	15.10	120	26.0	13.0
52	KUG 1416+257	14 18 25.60	+25 30 06.7	4450	15.70	15.07	14.50	145	6.9	3.5
56	MCG +06-33-026	15 11 14.09	+37 02 37.7	16 499	15.69	14.81	14.49	80	25.6	12.8
60C		15 47 24.32	+38 55 50.4	23 519	17.71	17.29	17.02	56	36.3	18.1
61		15 49 54.81	+09 49 43.1	13 753	15.78	14.81	14.50	140	21.4	10.7
67C	CGCG 225-097	17 17 44.13	+40 41 52.0	8325	15.28	14.25	14.01	165	12.9	6.5
69C	II Zw 092	20 48 05.67	+00 04 07.8	7396	16.22	15.36	14.93	34	11.6	5.8
260C	CGCG 068-056	11 45 30.25	+09 43 44.8	6399	15.31	14.48	14.23	18	10.0	5.0

**Notes.** <sup>(a)</sup> The numbers are followed by C when kinematically confirmed. PA is the position angle of the polar ring (with uncertainty  $\pm 5^\circ$ ). The kinematics were obtained for SPRC-7 by Brosch et al. (2010), for SPRC-33 by Bettoni et al. (2010), for SPRC-67 by Merkulova et al. (2012), for SPRC-10, 14, 39, 60, and 69 by Moiseev et al. (2011), for SPRC-260, by Khoperskov et al. (2013). Magnitudes are from SDSS.

**Table 2.** Molecular data and stellar mass of the five detected PRGs.

SPRC No.	Area K km s <sup>-1</sup>	$V$ km s <sup>-1</sup>	$\Delta V^a$ km s <sup>-1</sup>	$T_{\text{mb}}^b$ mK	$M(\text{H}_2)^c$ 10 <sup>9</sup> $M_\odot$	$M^*$
14C	0.81 ± 0.1	5 ± 11	165 ± 24	4.6	8.4	23
	1.04 ± 0.1	-26 ± 5	127 ± 12	7.7		
69C	0.71 ± 0.1	6 ± 15	193 ± 40	3.5	4.5	11
	0.68 ± 0.1	-17 ± 10	128 ± 23	5.0		
42	0.91 ± 0.1	-22 ± 16	231 ± 34	3.6	5.2	7
	0.82 ± 0.2	-24 ± 14	131 ± 36	5.8		
47	0.73 ± 0.1	-59 ± 61	550 ± 110	1.3	7.3	40
	0.72 ± 0.2	74 ± 57	479 ± 95	1.5		
48	0.65 ± .05	21 ± 17	380 ± 50	1.7	21.5	70
	0.72 ± 0.2	142 ± 67	450 ± 143	1.6		

**Notes.** For each object, the first line displays the CO(1–0) and the second line the CO(2–1) results. Results of the Gaussian fits. <sup>(a)</sup> FWHM. <sup>(b)</sup> Peak brightness temperature. <sup>(c)</sup> Obtained with the standard MW conversion ratio.

confirmed PRGs. Table 2 reports all line parameters for the detections, and the upper limits for the non-detections are reported in Table 3. Integrated signals and velocity widths have been computed from Gaussian fits. These also give the central velocities, with respect to the optical redshift of Table 1. The upper limits are computed at  $3\sigma$ , assuming a common line width of 300 km s<sup>-1</sup> and getting the rms of the signal over 300 km s<sup>-1</sup>.

The detection rate of  $24 \pm 9\%$  is comparable to that found for early-type galaxies, for which the gas content is believed to be due to recent accretion, as was found in the SAURON and ATLAS<sup>3D</sup> samples (e.g. Combes et al. 2007; Young et al. 2011).

One problem in the interpretations of the data is the size of the CO beams, which are sometimes smaller than the total extent of the polar rings. Table 1 lists the values of the two beams in kpc on the major axis of the galaxies. For the CO(1–0) beam,

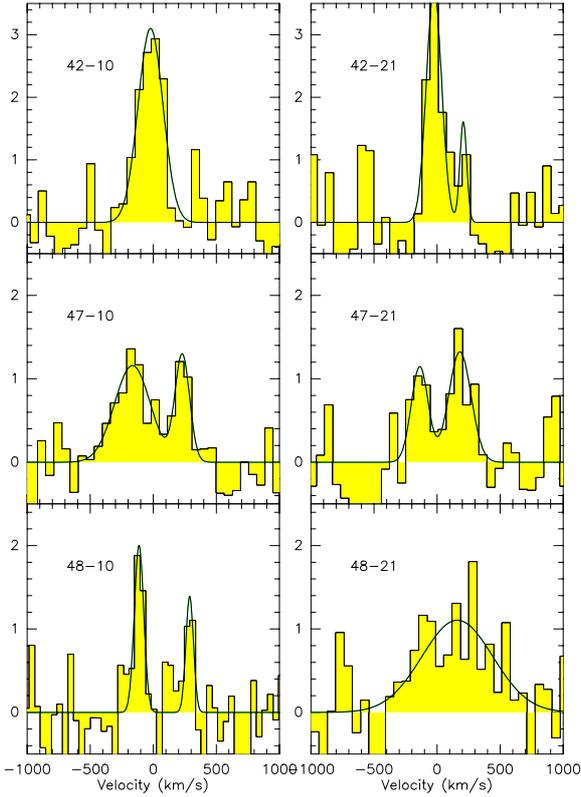
two detected galaxies, SPRC-42 and SPRC-47, are particular in this case, where the H<sub>2</sub> mass derived in Table 2 might only be a lower limit. The shape of the CO(1–0) and CO(2–1) velocity profiles are not the same, since both lines resolve the polar ring differently. Among the upper limits, four polar rings are also in this case, SPRC-33, 52, 67 and 69. A full map would be required to settle the issue.

In all the detected galaxies, we interpret the CO emission as coming from the polar-ring system, since it is always the bluer one (cf. Fig. 1). All five of the detected polar rings are almost edge-on, which minimizes the errors done in correcting for inclination the observed linewidths, to obtain indicative rotational velocities (cf. Fig. 4).

The line widths detected are in average 304 km s<sup>-1</sup> full width at half maximum (FWHM). Two of the PRGs, P47 and P48, clearly show double-horn profiles, indicative of rotating disks or rings. For two of the detected galaxies, the rotational velocity has also been estimated in the ionized gas (Moiseev et al. 2011). For SPRC-14 the ionized gas data in projection on the sky has a symmetrized maximal line-of-sight rotation velocity of 160 km s<sup>-1</sup>, in good agreement with the CO(1–0) value of  $165 \pm 24$  km s<sup>-1</sup>. The polar ring is, however, asymmetric, and with an extension on the NE side, where the velocity reaches up to  $V_{\text{max}} = 262 \pm 11$  km s<sup>-1</sup> (H $\alpha$ ) and  $268 \pm 5$  (NII).

For SPRC-69 the ionized gas velocity field yields  $V_{\text{max}} = 178 \pm 3$  km s<sup>-1</sup>, (172 after projecting with the inclination of  $76^\circ$  of the polar ring) a value also in agreement with the CO(1–0) value  $193 \pm 40$  km s<sup>-1</sup>.

These comparisons show that we are not underestimating too much the maximum velocities of the polar rings, even though the CO beam might not encompass all the optical extent of it. This might come from the fact that the maximum velocity is reached already at small radii, especially for the molecular gas, which is more concentrated towards the center. We have plotted our detected objects in the Tully-Fisher diagram of Fig. 4,



**Fig. 2.** CO spectra of the detected PRG galaxies, not yet kinematically confirmed. *Left-hand panels* are the CO(1–0), *right-hand panels* CO(2–1) emission. The velocity scale is relative to the redshift displayed in Table 1. The vertical scale is  $T_{\text{mb}}$  in mK.

in comparison with normal spirals from Giovanelli et al. (1997) and other PRGs from Iodice et al. (2003). We note that we have corrected the velocity for AM 2020–504, which is erroneous in Iodice et al., replacing it with the value from Whitmore et al. (1990) and van Driel et al. (2002). We have converted the  $i$  to  $I$  magnitudes by the formula

$$I - i = -0.0307(r - i)^3 + 0.1163(r - i)^2 - 0.3341(r - i) - 0.3584$$

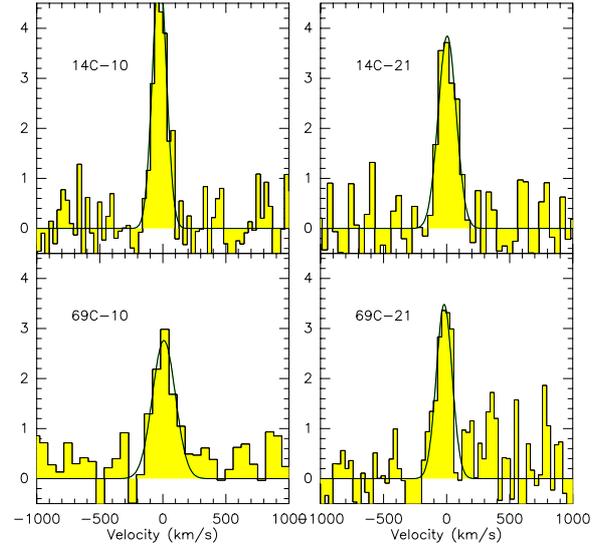
from Ivezić et al. (2007). The CO-detected PRGs show the same tendency to lie to the right of the main relation, i.e. their velocities are too high. Since the velocities determined from CO are lower limits (because of the restricted beam), this result is robust.

#### 4.2. CO luminosity and $H_2$ mass

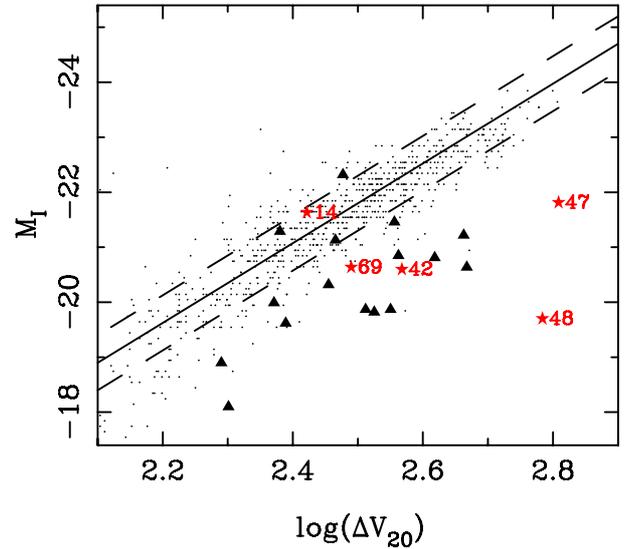
We have simultaneously observed the two first lines of the CO rotational ladder, and it is interesting to compare them, to have an idea of the excitation of the gas. Therefore, we compute  $L'_{\text{CO}}$ , the special unit CO luminosity, through integrating the CO intensity over the velocity profile. This luminosity, expressed in units of  $\text{K km s}^{-1} \text{pc}^2$ , will give the same value irrespective of  $J$ , if the CO lines are saturated and have the same brightness temperature. This CO luminosity is given by

$$L'_{\text{CO}} = 23.5 I_{\text{CO}} \Omega_{\text{B}} \frac{D_{\text{L}}^2}{(1+z)^3} \text{ K km s}^{-1} \text{ pc}^2, \quad (1)$$

where  $I_{\text{CO}}$  is the intensity in  $\text{K km s}^{-1}$ ,  $\Omega_{\text{B}}$  the area of the main beam in square arcseconds, and  $D_{\text{L}}$  the luminosity distance in Mpc.



**Fig. 3.** Same as Fig. 2 for the two kinematically confirmed and CO-detected PRGs.



**Fig. 4.** Tully-Fisher relation for our detected PRGs (red stars), compared with other PRGs (black triangles, Whitmore et al. 1990; van Driel et al. 2002; Iodice et al. 2003), and normal spirals (black dots, Giovanelli et al. 1997). The  $I$  absolute magnitudes, with uniform photometry and distance corrections, are plotted vs. observed rotation velocities (full width at 20% power), in the polar rings.

In most cases (15 out of the 21 objects in the sample) the beam in CO(1–0) is large enough that it is likely to encompass all the emission of the polar-ring system; however, it is not the same in CO(2–1), and only the CO(1–0)-derived  $H_2$  masses should be trusted. For the detected objects, the integrated intensities are always comparable between the CO(1–0) and CO(2–1) lines, as can be seen in Table 2. For point sources, with saturated and thermalized CO lines, the ratio should be as high as 4, in favour of the CO(2–1). The fact that intensities are comparable can be interpreted either in terms of an extended emission, or a sub-thermal excitation, or both.

We have computed the molecular mass from the CO(1–0) flux, using  $M_{H_2} = \alpha L'_{\text{CO}}$ , with  $\alpha = 4.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ , the standard factor for nearby quiescent galaxies like the Milky Way.

**Table 3.** Upper limits.

SPRC No.	Line	$\nu_{\text{obs}}$ [GHz]	rms [mK]	$L'_{\text{CO}}/10^9$ [K km s <sup>-1</sup> pc <sup>2</sup> ]	$M(\text{H}_2)$ [ $10^9 M_{\odot}$ ]
7C	CO(10)	108.7	0.8	1.16	5.3
	CO(21)	217.4	1.6	0.72	3.3
10C	CO(10)	110.6	0.6	0.43	2.0
	CO(21)	221.1	1.1	0.25	1.1
13	CO(10)	111.7	0.9	0.36	1.6
	CO(21)	223.4	1.2	0.15	0.7
15	CO(10)	111.4	0.7	0.33	1.5
	CO(21)	222.9	0.8	0.12	0.5
17	CO(10)	112.3	0.7	0.19	0.9
	CO(21)	224.6	0.7	0.06	0.3
24	CO(10)	110.1	0.8	0.71	3.2
	CO(21)	220.1	1.4	0.38	1.8
29	CO(10)	110.0	0.7	0.63	2.9
	CO(21)	220.1	1.1	0.31	1.4
31	CO(10)	109.8	0.7	0.69	3.2
	CO(21)	219.6	1.5	0.46	2.1
33C	CO(10)	114.7	1.1	0.90	4.1
	CO(21)	229.5	0.9	0.23	1.0
39C	CO(10)	111.9	0.7	0.24	1.1
	CO(21)	223.9	0.7	0.07	0.3
52	CO(10)	113.6	0.9	0.08	0.3
	CO(21)	227.2	1.1	0.03	0.1
56	CO(10)	109.2	0.9	1.09	5.0
	CO(21)	218.5	1.3	0.49	2.2
60C	CO(10)	106.9	0.6	1.49	6.9
	CO(21)	213.8	0.9	0.70	3.2
61	CO(10)	110.2	0.6	0.50	2.3
	CO(21)	220.4	1.1	0.29	1.3
67C	CO(10)	112.1	0.7	0.21	1.0
	CO(21)	224.3	1.0	0.09	0.4
260C	CO(10)	112.9	1.0	0.18	0.8
	CO(21)	225.7	0.9	0.05	0.2

**Notes.** The rms are in  $T_{\text{A}}^*$  in channels of 30 km s<sup>-1</sup>. The upper limits in  $L'_{\text{CO}}$  and  $M(\text{H}_2)$  are at  $3\sigma$  with an assumed  $\Delta V = 300$  km s<sup>-1</sup>.

The molecular gas masses are listed in Table 2 and the upper-limits in Table 3.

The average CO luminosity for the five galaxies detected is  $L'_{\text{CO}} = 2.0 \times 10^9$  K km s<sup>-1</sup> pc<sup>2</sup>, corresponding to an average H<sub>2</sub> mass of  $9.4 \times 10^9 M_{\odot}$ . These gas masses are relatively high, and we now compare them to stellar masses for each system.

#### 4.3. Stellar mass and gas fraction

We compute stellar masses from observed optical (SDSS) and near infrared (2MASS) magnitudes, using calibrated relations between mass-to-light ratios and colours (see e.g. Bell et al. 2003). The multi-wavelength luminosities were K-corrected according to the colours (cf. Chilingarian et al. 2010). Stellar masses are displayed in Table 2. The gas fractions derived from these stellar masses show large variations, between 15% and 43%, with an average of 27%. These gas fractions are quite high, compared to normal spirals at the same redshifts. The selection of bright PRGs at these distances means therefore the selection of galaxies that have just accreted a large amount of gas mass.

## 5. Summary and discussion

We have presented our CO survey in 21 PRGs, observed with the IRAM-30 m telescope. Five galaxies were detected, and among them two kinematically confirmed PRGs. The detection rate of  $24 \pm 9\%$  is comparable to early-type galaxies, where the gas is thought to have been recently accreted. The first two CO lines were observed, and the  $L'(\text{CO})$  luminosities in CO(2–1) are lower than in CO(1–0), indicating either a subthermal gas, and/or a gas extent larger than the  $\sim 12''$  CO(2–1) beam. Assuming a standard CO-to-H<sub>2</sub> conversion factor, the average molecular gas mass is found to be  $9.4 \times 10^9 M_{\odot}$ . The average ratio between gas and stellar mass is 0.4, or the average gas fraction is 27%. This high fraction means that bright PRGs have just accreted a large amount of gas.

We interpret our CO detections as coming from the polar-ring systems in the detected galaxies, since it is the bluer and younger component. Deriving the rotational velocity of the gas from the CO profile, we have placed our observed galaxies in the Tully-Fisher diagram, allowing us to compare them with the control sample of normal spirals. The new detected objects confirm the offset position of PRGs already noticed by Iodice et al. (2003).

In Fig. 4, one of the PRGs falls in the expected range for a spherical potential (SPRC-14), two are mildly offset (SPRC-69 and SPRC-42), and two are very far from the usual relation, with very broad velocities (SPRC-48 and SPRC-47). This large scatter might indicate different formation mechanisms for the systems, and at least four out of the five should have their dark matter halo aligned with the polar plane. The position of the five PRGs in the TF diagram does not appear related to the mass ratio between the polar disk/ring and the host. The galaxies SPRC-42 and SPRC-69 have polar structures brighter than their hosts, while SPRC-14 and SPRC-48 are comparable, and SPRC-47 is weaker than its host. This was also the case in the previous PRGs (Iodice et al. 2003). There is no obvious relation with the PR spatial extent either.

The two most extreme cases (SPRC-47 and SPRC-48) must have a very flattened dark-matter system, as flat as a disk. This result is however uncertain, since the mass distribution is not yet known, and the CO beam does not cover the whole polar disk: the velocity could be higher in the center, and the flat portion of the rotation curve be lower. A full CO map at high spatial resolution is required to conclude.

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