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NEAR INFRARED PHOTOMETRY OF VIOLENT STAR FORMATION REGIONS

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RESUMEN

Se presenta la fotometría de banda ancha en el cercano infrarrojo e índices de CO para un número apreciable de regiones con formación estelar violenta. Se confirma la existencia de una buena correlación entre W(Hβ) y el color IR. La interpretación de esta relación como una secuencia de edad implicaría una correlación entre el índice de color CO y W(Hβ), la cual no se encuentra. Se argumenta sin embargo que esta falta de correlación es el resultado casi seguro del uso de filtros de banda angosta para determinar los índices CO en objetos que presentan espectros con fuertes líneas de emisión.

ABSTRACT

Near infrared broad band photometry and CO indices for a significant number of Violent Star Formation Regions are presented. The existence of a narrow correlation between W(Hβ) and IR colour is confirmed. The interpretation of this relation as an age sequence implies a correlation between CO index and W(Hβ) which is not found. It is argued however that this failure is most likely a consequence of using narrow band filters to determine CO indices in objects with strong emission-line spectra.

Key words: **PHOTOMETRY – INFRARED-SOURCES – STAR-FORMATION**

I. INTRODUCTION

Violent Star Formation Regions (*VSFRs*) are regions where thousands of massive stars have recently been formed in a small volume of space and over a time scale of only a few million years (Melnick, Terlevich, and Eggleton 1985; henceforth Paper I). *VSFRs* are ubiquitous in a variety of extragalactic systems, the best known types being the giant extragalactic H II regions (e.g., 30 Dor in the LMC and NGC 604 in M33; Melnick 1979) and starburst nuclei of galaxies (Balzano 1983). Another well known manifestation of *VSF* activity are "isolated extragalactic H II regions" or "H II galaxies" (Sargent and Searle 1970; Terlevich and Melnick 1981) which are dwarf galaxies whose luminosity at optical wavelengths is completely dominated by the *VSFR* or "burst of star formation" (Paper I). Recently, Terlevich and Melnick (1985) have shown that the optical spectra of both type 2 Seyferts and Liners can also be understood in terms of *VSFRs* in the nuclear region of early type galaxies and have presented evolutionary models showing that the spectra of high metallicity *VSFRs* evolve from normal, low-excitation H II regions to Seyferts and/or Liners as a consequence of the evolution of their most massive stars.

Clearly, the study of *VSFRs* appears to be the key to understanding a wide range of phenomena related to the formation and the evolution of galaxies. Moreover, by studying the systematic properties of *VSFRs* it is also possible to place stringent constraints on the theory of formation and evolution of massive stars (Terlevich and Melnick 1981; 1985; Melnick, Terlevich, and Campbell 1985), thus complementing studies of individual early type stars in the Galaxy and other galaxies of the Local Group (Garmany, Conti, and Chiosi 1982; Conti *et al.* 1983; Humphreys and McElroy 1984).

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Perhaps one of the most fundamental questions to ask about the nature of *VSFRs* is whether they are produced by single, isolated bursts of star formation and contain only young stars, or whether *VSF* activity is continuous (or cyclical) and therefore these objects contain substantial populations of intermediate age stars from previous star formation cycles. Since, by definition, *VSFRs* are objects where the visual luminosity is dominated by young stars, other wavelength regions should be used to search for an answer to this important ques-

TABLE 1

OBSERVATIONAL RESULTS

VSFR[a]	Galaxy[c]	Aperture Diameter	K_0	$(J-H)_0$	$(H-K)_0$	$(CO)_0$
0402-4333	NGC 1510	5\".3	12.99	0.54	0.19	0.02 ± 0.05
0440-3806	To 0440-381	7.1	14.07	0.50	0.19	...
0453-5326	NGC 1705-I	5.3	12.24	0.57	0.18	0.18 ± 0.02
		7.1	12.11	0.60	0.20	0.18 ± 0.02
0553+0323	II Zw 40	4.4	13.62	0.24	0.56	0.24 ± 0.06
		8.9	13.19	0.43	0.43	...
		10.6	12.84	0.29	0.52	-0.06 ± 0.10
0614-3735	To 0614-375	7.1	13.13	0.57	0.28	...
0633-4131	To 0633-413	7.1	14.94	0.39	0.17	...
0645-3740	To 0645-372	7.1	15.24	0.49	0.44	...
0842+1616	C8-28A	7.1	13.68	0.63	0.37	...
0957-2753	To 0957-278	7.1	13.75	0.55	0.15	0.21 ± 0.16
1004-2941 SE	To 1004-296 SE	4.4	13.68	0.52	0.24	0.19 ± 0.08
		5.3	13.30	0.53	0.22	0.13 ± 0.09
1004-2941 NW	To 1004-296 NW	4.4	13.21	0.49	0.44	0.16 ± 0.04
		5.3	13.01	0.47	0.34	0.11 ± 0.05
1053+0624	F 30	7.1	13.35	0.62	0.16	...
1147-2823	To 1147-283	7.1	14.67	0.52	0.25	...
1148-2019	C 1148-2020	4.4	15.28	0.15	0.48	...
		7.1	15.05	0.29	0.34	...
1247-2317	To 1247-232	7.1	14.92	0.55	0.43	...
1324-2741	To 1324-276	4.4	14.37	0.52	0.29	...
		7.1	13.48	0.46	0.13	0.00 ± 0.07
1345-4206	To 1345-420	7.1	14.43	0.46	0.25	...
1337-3123a	NGC 5253a	4.4	12.32	0.40	0.82	-0.04 ± 0.63
		7.1	11.74	0.41	0.61	0.03 ± 0.04
1337-3123b	NGC 5253b	4.4	13.20	0.56	0.11	0.14 ± 0.05
		7.1	12.19	0.52	0.21	0.18 ± 0.01
1337-3123c	NGC 5253c	7.1	11.96	0.49	0.28	0.17 ± 0.03
1337-3123d	NGC 5253d	4.4	13.87	0.62	0.24	0.10 ± 0.13
1400-4110	NGC 5408	5.3	14.20	0.21	0.54	0.18 ± 0.14
		7.1	13.91	0.26	0.40	...
30 Dor	LMC	5.3	12.07	0.03	1.00	0.45 ± 0.06
Abell 30[b]	Milky Way	5.3	13.38	0.25	0.79	-0.27 ± 0.06

Notes: The subscripts in the broad-band colours and CO indices indicate that they have been corrected for galactic extinction.

a. Identification code based on the 1950.0 position of the objects taken from Terlevich *et al.* (1985).

b. Planetary nebula.

c. To = Tololo objective prism surveys, Smith, Aguirre and Zemelman (1976); Smith (1985; private communication).

C = Cambridge survey, Terlevich (1982).

F = Fairall (1980).

tion. This motivates the recent interest in near IR observations of *VSFRs* and related objects (Balzano and Weedman 1982; Thuan 1983; Campbell and Terlevich 1984; Glass and Moorwood 1985). The interpretation of the IR data however, has proven to be far from conclusive; Thuan (1983) has interpreted his observations in terms of an underlying old population of K and M giants and has adhered to the cyclic star formation scheme while Campbell and Terlevich (1984, henceforth CT) have shown that in *bona-fide VSFRs* (which comprise only part of Thuan's sample) the infrared data are consistent with what is expected from *VSFRs* of ages ranging from about 1 to 7 million years.

The purpose of this paper is to present new near IR observations of *VSFRs* that complement the data presented by CT. These new data are consistent with the interpretation of CT but show that IR spectroscopy in the 2-2.4μ wavelength region is required to reach a definite conclusion regarding the origin of the IR radiation from *VSFRs*.

II. OBSERVATIONS

The observations were obtained in 1984 February 16-19 with the Cassegrain IR photometer at the CTIO 4-m telescope. A description of the photometer is given by Frogel in the CTIO user's manual. We used the "D3" InSb dewar system and the standard broad-band J (1.28μ), H (1.65μ), K (2.20μ) filters plus narrow-band filters at 2.217μ and 2.375μ that define the CO index (Frogel *et al.* 1978). Background subtraction was achieved using the f/30 chopping secondary at a frequency of 3 Hz and a throw of 1 arcmin in RA.

Transformation to the standard "cold CIT" system (Frogel *et al.* 1978) was obtained by observing each night at least 10 standard stars, covering a wide range of colours and CO indices, selected from the list of Elias *et al.* (1982). The reductions were performed at the CTIO computer center at La Serena using a program kindly made available to us by Frogel. The results are presented in Table 1 where for each object, identified by a code giving the 1950 position, we give the aperture diameter, the broad-band colours and the CO indices, corrected for galactic extinction following CT. Typical errors in the broad band photometry are 2% or less and in no case was the error larger than 5%. The uncertainty of the CO strengths is given in the table. Unfortunately the CO observations were made difficult by an unusually high atmospheric water vapor content and could be obtained for only some of the objects.

III. DISCUSSION

a) *The (J–K) (H–K) Two Colour Diagram*

CT have presented a detailed discussion of the possible sources of near IR radiation in *VSFRs*. According to CT, the main contributors are gaseous emission (GE), both continuous and lines, luminous hot stars (HBB), cool evolved stars, mostly red supergiants (RSG) and emission from hot dust. CT have shown that the relative proportions of these ingredients that make up the near IR colours of *VSFRs* depend upon the ages of the regions. In Figure 1 we reproduce an adaptation of the $(J-H)_0$ vs $(H-K)_0$ two-colour diagram of CT where we have plotted our data together with the observations of CT.

Since, *a priori,* we do not know to what extent the near IR colours of the H II regions may be affected by dust-emission, and since the theoretical colours for pure gaseous emission may be affected by uncertainties in the transmission curves of the *JHK* bands (CT), we have observed a small, star-free region of the 30 Dor nebula to represent the expected *JHK* colours of the nebular component. Figure 1 shows that *VSFRs* define a region of the $(J-H)$ vs $(H-K)$ two-colour diagram that is enclosed by mixing lines connecting the dominant sources of IR radiation identified by CT but with the 30 Dor point defining the nebular and dust contributions. Since the $(J-H)$ colour of 30 Dor agrees very well with the

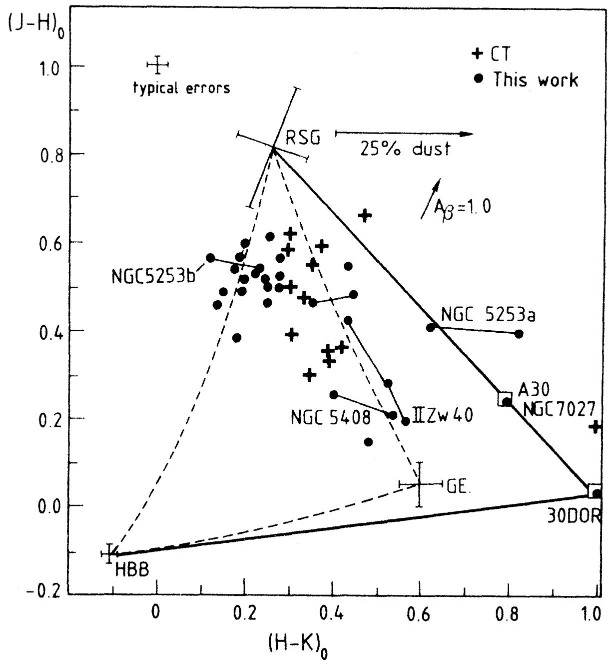

Fig. 1. Near IR two-colour diagram for *VSFRs*. The locii for a Hot (42500°K) Black-Body (HBB), pure nebular (GE) and cool stellar (RSG) infrared emission from Campbell and Terlevich (1985) have been plotted together with mixing lines adapted from that work (dashed lines). The vertical arrow represents the effect of assuming that 25% of the flux at K is emitted by warm dust at 200 K. The small arrow represents the effect of one magnitude of internal extincton at Hβ that is typically derived from the Balmer decrements of *VSFRs*. The thick solid lines encompass the region of the diagram where all *VSFRs* are expected to lie if their IR emission is a mixture of HBB, RSG and nebular emission as represented by a star-free spot in the 30 Doradus nebula. Data points linked by lines represent objects observed through more than one aperture.

theoretical calculation of CT, we conclude that the difference in $(H-K)$ colour is most likely due to dust emission (Fig. 1) and therefore that a significant fraction of the K-band luminosity of young *VSFRs* may be due to dust emission.

In order to quantify the analysis of the two-colour diagram, CT defined the index $(J-H)_0 - (H-K)_0$ that approximately measures the departure of the IR colours from the values expected for pure nebular gas emission. CT have shown that this index anticorrelates strongly with the equivalent width of the Hβ emission line in *VSFRs*, W(Hβ), and have interpreted this result in terms of an age effect. Figure 2 presents a plot of $(J-H)_0 -(H-K)_0$ as a function of W(Hβ) including our new data. The individual equivalent widths and data sources are given in Table 2. The W(Hβ) values have generally been measured with aperture sizes different from those used in the IR observations and this may introduce significant scatter in the correlation. However, our data clearly confirms the existence of a correlation between W(Hβ) and the IR index.

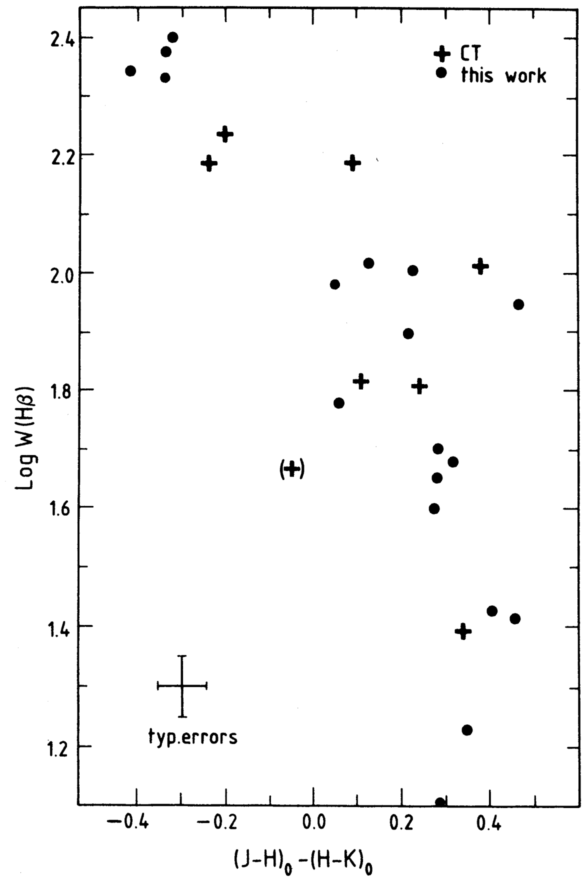

Fig. 2. Plots of the IR colour index $-(J-H)_0$ $(H-K)_0$ against the equivalent width of Hβ emission W(Hβ). The IR colour index approximately measures the departure of the observed colour from pure nebular emission while W(Hβ) is a good age indicator for *VSFRs*.

Since W(Hβ) is a well established age indicator for *VSFRs* (Dottori and Bica 1981; Terlevich, Melnick and Campbell 1985) CT concluded that the correlation between $(J-H)_0$-$(H-K)_0$ and W(Hβ) implies that the IR luminosity of *VSFRs* must be dominated by a young stellar population of ages, as indicated by W(Hβ), not greater than 10^7 years (about 10^6 yrs for II Zw 40 and 7×10^6 yrs for NGC 5253B). Clearly however, this correlation may also be interpreted assuming that the IR radiation is emitted only by old stars and nebular gas and that, as the H II region ages and the gaseous emission fades, the old stellar component becomes increasingly dominant producing the observed change in IR colour with age (CT). Although this explanation is difficult to reconcile with the fact that young *VSFRs* of widely different masses have essentially the same W(Hβ) and infrared colours, it cannot be ruled out solely on the basis of near IR broad band photometry. CT used the luminosity sensitive infrared CO index to argue that the near-IR luminosity of evolved (age $\sim 10^7$ yrs) *VSFRs* is mostly produced by young red supergiants. Unfortunately, however, CT were able to determine CO indices for only 3 objects and were therefore not able to confirm the expected correlation between CO index and W(Hβ).

b) *The CO Index*

The depth of the CO first overtone feature longward of 2.29μ has been shown by Frogel *et al.* (1978) to be sensitive to the effective gravity of late type stars ranging from CO $\geqslant$ 0.3 for M-supergiants to CO $\sim$ 0.15 for giants and CO $\sim$ 0 for dwarfs. This makes the CO index a useful age indicator for intermediate age star clusters (Frogel *et al.* 1975) and, as discussed by CT, should also make it a useful age indicator for very young systems due to the presence of red-supergiants. Unfortunately, the CO index as defined by Frogel *et al.* (1978) in terms of two narrow band filters centered at 2.2μ and 2.4μ may be contaminated by nebular Brackett line emission (Bγ, λ2.166μ) and depends rather strongly on redshift (Frogel *et al.* 1978). CT have avoided these problems by using CVF spectrophotometry to synthesize the CO index. However, this method is very time consuming and CT were able to determine CO indices for only 3 regions. Consequently we have tried here to follow a different approach; by combining narrow and broad band photometry at 2.2μ it is possible to determine the equivalent width of Bγ, W(Bγ), and therefore to estimate the nebular effect on the CO observations. Assuming that the continuum has no features in the 2.0 to 2.4μ region W(Bγ) can be calculated as,

$$W(B\gamma) = -\ \Delta\lambda_n \frac{1 - f.w}{1 - (b_0/n_0)\,w} \quad ,$$

where w is the ratio of counts between the 2.2μ (narrow) filter and the K (broad) filter. $\Delta\lambda_n$ is the width of

TABLE 2

DERIVED PARAMETERS

VSFR	Redshift	$(CO)_0^a$	W(Hβ)	Aperture	$W(B\gamma)_0^a$	Sources
0402-4323	0.003	0.03	17 Å	2"× 4"	70 Å	1,2,3
0440-3806	0.040	...	35	4 × 4	...	1,3
0453-5326	0.002	0.19/0.19	< 0	2 × 4	130/60	1,3
0553+0323	0.0028	0.25/-0.05	310	2 × 4	290/180	1,2
0614-3735	0.032	...	10	2 × 4	...	1,3
0633-4131	0.016	...	100	2 × 4	...	1,3
0645-3740	0.026	...	60	2 × 4	...	1,3
0842+1616	0.05	...	35	8 × 8	...	1,3
0957-2753	0.006	0.24	25	4 × 4	80	1,3
1004-2941 SE	0.004	0.21/0.15	50	2 × 4	60/0	1,3
1004-2941 NW	0.004	0.18/0.13	95	2 × 4	100/70	1,3
1053+0624	0.004	...	120	2 × 4	...	1,3
1147-2823	0.006	...	45	2 × 4	...	1,3
1148-2019	0.012	...	215	2 × 4	...	1,3
1247-2317	0.049	...	105	6 × 8	...	1,3
1324-2741	0.006	0.03	115	2 × 4	130	1,3
1345-4206	0.006	...	80	2 × 4	...	1,3
1337-3123a	0.002	-0.04/0.03	220	2 × 4	140/130	1,2,3
1337-3123b	0.002	0.14/0.16	25	2 × 4	180/150	1,2,3
1337-3123c	0.002	0.17	40	2 × 4	250	1,2,3
1337-3123d	0.002	0.10	50	2 × 4	300	1,2,3
1400-4110	0.001	0.18	240	2 × 4	210	1,2,3
30 Dor	0.000	0.45	...	...	430	...
A30	0.000	-0.27	...	...	20	...

Notes: a. Entries with more than one value correspond to objects measured with 2 apertures and are given in the order presented in Table 1.

Sources: 1. Campbell, Terlevich, and Melnick 1985.
2. Sandage and Tammann 1981.
3. Terlevich *et al.* 1985.

the narrow filter (990 A), f is the ratio of effective transmissions of the broad to the narrow filter and $b_0(n_0)$ is the peak transmission of the broad (narrow) filter at the redshifted wavelength of the line. In general n_0 and b_0 depend on the radial velocity of the source but we have restricted the observations to low redshift ($z < 0.01$) objects so b_0 may be considered to be constant. Since accurate transmission curves are not available, we have assumed $b_0/n_0 = 1$, that is a reasonable assumption as the narrow filter is approximately squared (Frogel, private communication). The value of f was determined from observations of standard stars to be 3.55 ± 0.01.

The results are presented in the last 2 columns of Table 2. We estimate systematic errors in the W(Bγ) values due to our choice of parameters to be of order 20%. An inspection of the data in that table shows that both objects with very low (old) and very large (young) Hβ equivalent widths have large CO indices. Following the discussion presented by CT, the CO indices of old (age ∿ 10^7 yrs) *VSFRs* are most likely due to the presence of RSG stars. Our results show that the large CO indices of young regions are due to Bγ emission as evidenced by their large W(Bγ) values, but they also show that evolved *VSFRs* may have large W(Bγ) values too Figure 3 presents a plot of the CO index as a function of W(Bγ).

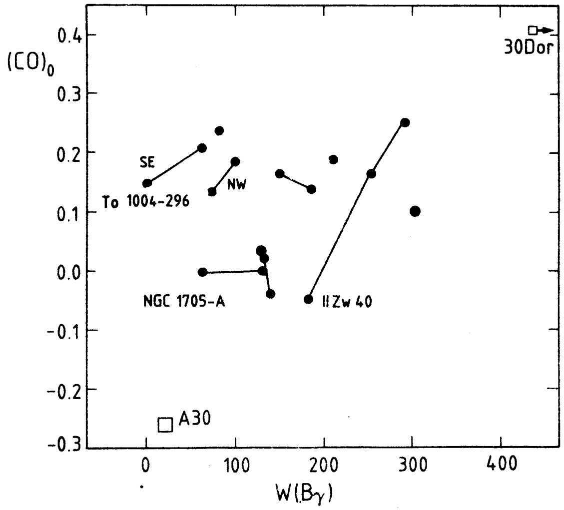

Fig. 3. Plot of the 2.2μ CO index versus the equivalent width of the Bγ line at 2.21μ. Data points linked by lines represent objects observed through more than one aperture.

The figure shows that the evolved *VSFR* NGC 5253B (age ∿ 7 Myr; CT) for which CT measured a *bona-fide* CO index of 0.25 ± 0.05 through an 8 arcsec aperture (our value through a 7 sec aperture is 0.17 ± 0.05), has W(Bγ) = 180 A indicating that a substantial fraction of *our* measured CO could be due to Bγ emission (a CO index of $(CO)_0 \cong 0.11$ is expected for a flat-continuum source with W(Bγ) = 100 A). But since the CO measurement of CT is not contaminated by Bγ we are forced to conclude that either our W(Bγ) scale is off by nearly 200 A or that there must be some feature within the *K*-band (2.0-2.4μ) besides Bγ. Since all the objects we observed have approximately the same redshift, and there are some objects that have *high* CO indices and *low* *W*(Bγ) values, we conclude that it is unlikely that our W(Bγ) values are affected by large calibration errors. Moreover, Moorwood (1985; private communication) has obtained CVF W(Bγ) values of 200 ± 60 A for II Zw 40 and 135 ± 20 A for NGC 5253 A that agree very well with our own determinations.

A clue may be obtained from NGC 1705-A. This is an evolved *VSFR* in the amorphous galaxy NGC 1705 that shows very weak Balmer emission lines at optical wavelengths (Melnick, Moles, and Terlevich 1985) and yet it has W(Bγ) = 100 A [$(CO)_0$ = 0.20 ± 0.02]. This is the only object for which we observed the H_2O index at 2.0μ (Frogel *et al.* 1978) because we did not expect large contamination by Bγ. This measurement, H_2O = 0.13 ± 0.05 shows that there are absorption features longwards (CO) and shortwards (H_2O) of 2.2μ. Thus, in this case W(Bγ) measures a continuum peak at 2.2μ of an equivalent width consistent with what we expect from the narrow band 2.2μ/2.4μ and 2.2μ/2.0μ count ratios. We conclude that the determination of reliable CO indices in strong emission-line objects requires detailed IR spectroscopy and cannot be done using filters.

IV. CONCLUSIONS

We have presented near IR observations of a significant number of *VSFRs*. We have used these data to confirm the correlation between the equivalent widths and IR colours found by Campbell and Terlevich (1985) but we have failed to find the correlation between CO index and W(Hβ) expected if the (colour-W(Hβ)) relation is an age effect due to the evolution of a young stellar population. We found that the youngest as well as the most evolved *VSFRs* may have large CO indices. While the large CO indices observed in very young regions were found to be due to contamination by Bγ nebular emission, we were not able to find a clear interpretation of the CO indices we determined for evolved *VSFRs*.

Our results clearly show that it is not possible to define *bona-fide* CO indices of strong emission-line objects using filters, and that high resolution spectroscopy of *VSFRs* is required to make further progress in understanding the infrared properties of violent star formation activity.

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Note added in proof: Recently, Rieke *et al.* (1985; *Ap. J.*, **290**, 116) have reported the detection of strong H_2 emission lines at 2.1μ in the starburst galaxies Arp 220 and NGC 6240. These observations suggest that the large W(Bγ) values we find in evolved H II galaxies may be due to molecular hydrogen emission possibly excited by supernova shocks.

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