

# On the star formation history of IZw 18\*

F. Legrand<sup>1,2</sup>

<sup>1</sup> Institut d'Astrophysique de Paris, CNRS, 98bis boulevard Arago, 75014 Paris, France

<sup>2</sup> Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Apartado Postal 51 y 216, 72000 Puebla, Mexico

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**Abstract.** It has been suggested that a continuous low star formation rate has been the dominant regime in IZw 18 and in dwarf galaxies for the lifetime of these objects (Legrand et al. 1999). Here, we discuss and model various star-forming histories for IZw 18. Particularly, we show that if the metallicity observed in IZw 18 results from starburst events only, the observed colors constrain the fraction of the metals ejected from the galaxy to be less than 50–70%. We demonstrate that the continuous star formation scenario reproduces the observed parameters of IZw 18. A continuous star formation rate (SFR) of about  $10^{-4} M_{\odot} \text{ yr}^{-1}$  during 14 Gyr reproduces precisely the observed abundances. This SFR is comparable with the lowest SFR observed in low surface brightness galaxies (Van Zee et al. 1997c). Generalized to all galaxies, the low continuous SFR scenario accounts for various facts: the presence of star formation in quiescent dwarfs and LSBG, the metallicity increase with time in the most underabundant DLA systems, and the metal content extrapolations to the outskirts of spiral galaxies. Also the apparent absence of galaxies with a metallicity lower than IZw 18, the apparent absence of HI clouds without optical counterparts, and the homogeneity of abundances in dwarf galaxies are natural outcomes of the scenario. This implies that, even if starbursts are strong and important events in the life of galaxies, their more subdued but continuous star formation regime cannot be ignored when accounting for their chemical evolution.

**Key words:** ISM: jets and outflows – galaxies: abundances – galaxies: individual: IZw 18 – galaxies: ISM

## 1. Introduction

A challenge of modern astrophysics is the understanding of galaxies' formation and evolution. In this exploration, low-mass dwarfs and irregular galaxies have progressively reached a particular place. Indeed, in hierarchical clustering theories these galaxies are the building blocks of larger systems by merging (Kauffmann et al. 1993; Pascarella et al. 1996; Lowenthal et al. 1997). Moreover, as primeval galaxies may undergo rapid and strong star formation events (Partridge & Peebles 1967), nearby dwarf starburst

galaxies or Blue Compact Galaxies (BCDG) of low metallicity can also be considered as their local counterparts. Therefore the study of low redshift starbursts is of major interest for our understanding of galaxies formation and evolution.

As BCDG presently undergo a strong star formation (which cannot be maintained during a long time), but generally present a low metallicity indicating a low level of evolution, Searle & Sargent (1972) have proposed that these systems are young in the sense that they are forming stars for the first time. An alternative is that they have formed stars during strong starburst events separated by long quiescent periods. However, most dwarf starburst galaxies show an old underlying population indicating that they have also formed stars in the past (Thuan 1983; Doublie 1998). Thus they are not “young”.

Among starbursts, IZw 18, as the lowest metallicity galaxy known locally, could be considered as the best candidate for a truly “young” galaxy. However, recent studies have shown that even this object is not forming stars for the first time. Color magnitude diagrams have revealed the presence of stars older than 1 Gyr (Aloisi et al. 1999). Legrand et al. (1999) have shown that the extreme homogeneity of abundances throughout the galaxy (see also Van Zee et al. 1998) cannot be explained by the metals ejected from the massive stars formed in the current burst (see also Tenorio-Tagle 1996), thus indicating previous star formation. Then we need to constrain this previous star formation and specify its nature.

It is generally accepted that the enrichment of the ISM arises by burst phases. In the case of IZw 18, Kunth et al. (1995) have shown that one single burst with intensity comparable to the present one is sufficient to reproduce the observed abundances. However metals ejected by massive stars could escape the galaxy, if its total mass is lower than  $10^8 M_{\odot}$  (Mac Low & Ferrara 1999). The metallicity is then no longer a measure of the number of bursts. On the other hand, if the total mass of the galaxy amounts  $10^9 M_{\odot}$  the metals are likely to be retained (Silich & Tenorio-Tagle 1998). As the total mass of IZw 18 is likely to lie between these values (Viallefond et al. 1987; Van Zee et al. 1998), the escape of a fraction or of the totality of the newly synthesized metals during a burst cannot be excluded. In such a case several bursts are needed to account for the observed metallicity, their number depending on the fraction of metals leaving the galaxy. Nevertheless, even if metals escape, stars are likely to remain bound and for an increasingly larger number of bursts, the old underly-

Send offprint requests to: F. Legrand (legrand@iap.fr)

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ing stellar population will appear progressively redder. Thus the number of previous bursts is limited, considering the extremely blue color of BCDG.

Between starburst events, BCDG are likely to appear as Low Surface Brightness Galaxies (LSBG). However, studies of the latter (Van Zee et al. 1997c) showed that despite their low gas density, they do not have a zero star formation rate (SFR). LSBG indeed present a low and possibly continuous SFR. This led Legrand et al. (1999) to propose that a continuous low SFR over a Hubble time as responsible for the observed metallicity level in the most metal-poor objects like IZw 18.

Several studies of the past star formation history of BCDG, and specifically IZw 18, have been carried out. Most have dealt with their chemical evolution (Chiosi & Matteucci 1982; Carigi et al. 1995; Kunth et al. 1995) or with their spectrophotometric properties (Mas-Hesse & Kunth 1991; Leitherer & Heckman 1995; Stasinska & Leitherer 1996; Cervino & Mas-Hesse 1994; Mas-Hesse & Kunth 1999), but rarely with both. Moreover, solely the influence of bursts has been studied up to now, and the low continuous SFR of inter-burst phases has been ignored.

We used a spectrophotometric model coupled with chemical evolution in order to constrain both the abundances and the colors of the galaxies. We also investigated the effect of a continuous and low star formation regime. A preliminary study (Legrand & Kunth 1998) showed that this scenario is plausible. Here we present detailed calculations, results and their implications. The model and the observational data used are described in Sect. 2. The different models, including the investigation of mass loss effect and the continuous star formation rate model are presented in Sect. 3. Consequences and generalization of the continuous SFR hypothesis are discussed in Sect. 4.

## 2. Modelling the star formation history in IZw 18

In order to investigate the star formation history of IZw 18, we used the spectrophotometric model coupled with the chemical evolution program “STARDUST” described by Devriendt et al. (1999). The advantage of this model is that both the metallicity and the spectral properties of a galaxy are monitored through time.

### 2.1. The model

The main features of the model are the following:

- A normalized  $1 M_{\odot}$  of baryonic matter galaxy is considered.
- The SFR and the IMF are fixed and used to evaluate at each time the number of stars of all masses formed.
- The stellar lifetimes are taken into account, *i.e.*, no instantaneous recycling approximation is used. Metals ejected (C, O, Fe and the total metallicity) are calculated at each time step as well as the number of stars of each mass. The chemical and spectroscopic evolution is followed in time.
- A fraction of the metals produced by the massive stars ( $M \geq 9 M_{\odot}$ ) can be expelled from the galaxy and do not contribute to the enrichment.
- The fraction of the produced metals remaining into the galaxy is assumed to be immediately and uniformly mixed with the interstellar medium. We must keep in mind that there may be a time delay between their production and their visibility.
- The newly formed stars have the metallicity of the gas at the time of their birth.
- The spectrum as a function of time is computed by summing the number of stars multiplied by their individual spectra. The nebular emission is not included in the model.
- The model uses the evolutionary tracks from the Geneva group (Schaller et al. 1992; Charbonnel et al. 1996). The yields are from Maeder (1992) for the massive stars ( $M \geq 9 M_{\odot}$ ) and from Renzini & Voli (1981) for the lower mass stars. All the metals produced are ejected (Case A of Maeder 1992).
- The stellar output spectra is computed using the stellar libraries from Kurucz (1992) supplemented by Bessel et al. (1989, 1991) for M Giants, and Brett (1995) for M dwarfs.
- We used a typical IMF described as a power law in the mass range  $0.1-120 M_{\odot}$ .

$$\phi(m) = a.m^{-x} \quad (1)$$

A constant index  $x$  of 1.35 was used (Salpeter 1955). We now have some indications that the IMF may flatten at low masses, maybe below  $0.3 M_{\odot}$  (Elmegreen 1999; Scalo 1998). As the stars in this range ( $0.1-0.3 M_{\odot}$ ) do not contribute significantly to the enrichment of the ISM, nor to the colors, this will only act on the normalisation of the SFR in the sense that forming less low mass stars will decrease the total SFR requested to reproduce the observed abundances. However, as the SFR quoted by Van Zee et al. (1997b,c) and reproduced in Table 1 are computed using a Salpeter IMF down to  $0.1 M_{\odot}$  we used this value in the model in order to compare our results with these previous studies. Finally, their upper mass limit is  $100 M_{\odot}$  (against  $120 M_{\odot}$  in our models). However, the upper mass limit of the IMF do not affect strongly the derivation of the SFR but can modify the abundances. Thus using a Salpeter IMF ranging from  $0.1 M_{\odot}$  to  $120 M_{\odot}$  appears as a good compromise to study abundances and compare SFR with previous studies.

- Two regimes of star formation have been investigated:
  - A continuous star formation during which the SFR is low and directly proportional to the total mass of available gas.
  - A burst of star formation during which all the stars are formed in a rather short time.

### 2.2. Comparison of the model with IZw 18

As the model is normalized to one solar mass of gas, we had to multiply the parameters by the mass of IZw 18 in order to compare our results with the observations. However, this normalization appears only in the value of the SFR and in the absolute magnitude predictions; the colors reported are independent of the choice of the mass of the galaxy.

**Table 1.** Comparison between the SFR measured in quiescent dwarfs and LSBG and the continuous SFR predicted for IZw 18.

Name	Type <sup>a</sup>	Mb	$M_{HI}$	SFR	$\frac{SFR}{M_{HI}}$	ref <sup>b</sup>
		$10^7 M_{\odot}$	$M_{\odot}$	$M_{\odot}/yr$		
UGCA20	Irr/LSBG	-14.9	25	0.0083	3.32e-11	V97c
UGC2684	dW/LSBG	-13.7	15	0.0015	1.00e-11	V97c
UGC2984	?/LSBG	-18.4	500	0.35	7.00e-11	V97c
UGC3174	Irr/LSBG	-15.7	61	0.0086	1.41e-11	V97c
UGC5716	dSp/LSBG	-16.3	140	0.023	1.64e-11	V97c
UGC7178	dI/LSBG	-16.6	140	0.022	1.57e-11	V97c
UGC11820	dSp/LSBG	-17.7	440	0.074	1.68e-11	V97c
UGC191	dSp/qui	-18.2	320	0.15	4.69e-11	V97c
UGC300	dWf/LSBG	-16.5	93.3	0.03	3.26e-11	V97b
UGC521	Irr/LSBG	-15.8	95.5	0.023	2.41e-11	V97b
UGC634	dSp/qui	-17.7	470	0.029	6.17e-12	V97c
UGC891	dWf/qui	-16.3	100	0.014	1.40e-11	V97c
UGC1175	?/qui	?	102	0.0037	3.63e-12	V97b
UGC2162	dI/qui	?	71	0.0059	8.31e-12	V97b
UGC2535	dI/qui	?	275	0.003	1.09e-12	V97b
UGC3050	S/qui	?	479	0.13	2.71e-11	V97b
UGC3672	Irr/LSBG	-16.6	129	0.021	1.63e-11	V97b
UGC4660	dSp/LSBG	-17.8	363	0.025	6.89e-12	V97b
UGC4762	dI/qui	?	100	0.0099	9.90e-12	V97b
UGC5764	dI/qui	-13.9	34	0.0098	2.88e-11	V97c
UGC5829	dI/qui	?	182	0.080	4.40e-11	V97b
UGC7300	dI/qui	?	129	0.016	1.24e-11	V97b
UGC8024	dI/qui	?	49	0.0019	3.88e-12	V97b
UGCA357	dI/LSBG	-16.3	190.5	0.034	1.79e-11	V97b
UGC9128	dI/qui	?	3.55	0.00017	4.79e-12	V97b
Haro43	S/LSBG	-17.1	229	0.092	4.02e-11	V97b
UGC9762	dSp/LSBG	-18.0	479	0.05	1.04e-11	V97b
UGC10281	dWf/LSBG	-17.1	67.6	0.012	1.78e-11	V97b
IZw 18 <sup>c</sup>	dI	-13.92	6.9	0.0001	1.45e-12	
IZw 18 <sup>c</sup>	dI	-13.92	2.6	0.0001	3.85e-12	

<sup>a</sup> Morphological type / LSBG or quiescent dwarf (qui)<sup>b</sup> V97b: Van Zee et al. (1997b); V97c: Van Zee et al. (1997c)<sup>c</sup> The two values given depends if the total or only the main component HI mass is adopted.

The initial mass of gas in IZw 18 must lie between  $6.9 \cdot 10^7$  and  $8 \cdot 10^8 M_{\odot}$ , which are respectively the mass of HI and the dynamical mass measured by Lequeux & Viallefond (1980). However, if only the main component is considered, the mass must be taken between  $2.6 \cdot 10^7$  (HI) and  $2.6 \cdot 10^8$  (dynamical mass) as measured by Van Zee et al. (1998). The initial mass of gas in IZw 18, in the absence of infall, was higher than the mass of HI because of the presence of stars and perhaps molecular  $H_2$  (Lequeux & Viallefond 1980). As dark matter can represent a non negligible fraction of the total dynamical mass, the mass of (baryonic) gas can be lower than the dynamical mass. We adopted a value of  $10^8 M_{\odot}$  for the initial mass of gas in IZw 18.

The model produces both the abundances and the spectra. We used the spectrum to derive the expected colors in (U-B), (B-V) and (V-K). We have adopted for comparison with the observed abundance values reported by Garnett et al. (1997) for C and Skillman & Kennicutt (1993) for O. Most of the

published colors for IZw 18 are relatively old (Huchra 1977; Thuan 1983), and have not been corrected for the nebular contribution. Salzer (1998) has recently measured the colors of IZw 18 and corrected for the nebular contribution. As our model does not include the nebular contribution, we adopted Salzer's values for comparison, *i.e.*,  $(U - B) = -0.88 \pm 0.06$  and  $(B - V) = -0.03 \pm 0.04$ ; Thuan (1983) has estimated that the flux measured in the IR was mainly of stellar in origin. We thus adopted his value for  $(V-K)=0.57 \pm 0.23$ .

Finally, the model used have been compared by Devriendt et al. (1999) with two similar models, *i.e.*, PE-GASE (Fioc & Rocca-Volmerange 1997) and GISSEL (Bruzual A. & Charlot 1993), and no differences larger than 0.1 magnitude were found; this was considered the intrinsic uncertainty of the modeling process.

### 3. Results of the modelisation

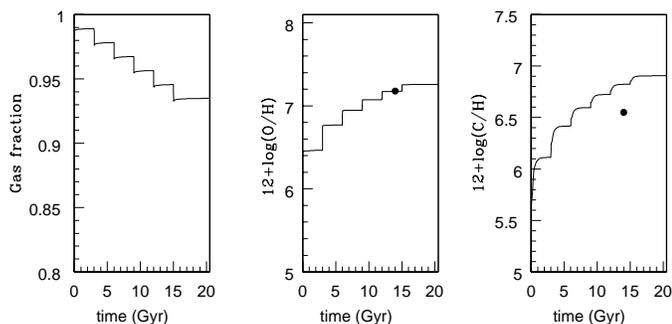
#### 3.1. Enrichment by one previous burst

It is generally admitted that the starburst events are the main contributors to the enrichment of the ISM. We thus used the model to evaluate the characteristics of a single burst to reproduce the observed oxygen abundance in IZw 18. Taking the uncertainties into account, we found, like previous studies (for example Kunth et al. 1995), that the present day abundances can be reproduced by a single burst, previous to the current one, with a SFR of  $0.065 M_{\odot} yr^{-1}$  during 20 Myr. Moreover, the contribution of this old underlying population is too faint to modify significantly the colors of the galaxy which are currently dominated by the newly formed massive stars. This model can reproduce all the observations.

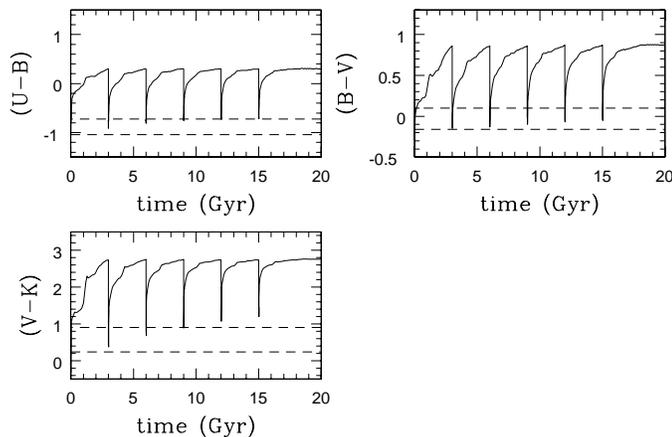
However, some simple arguments can rule out this model. Indeed, we assumed that between bursts, the SFR is equal to zero, which is certainly wrong. We will demonstrate below that even a low but continuous SFR between bursts, as observed in LSBG, is likely to produce significant enrichment. Moreover, the kinetic energy liberated in such a burst is high (about  $10^{40} erg s^{-1}$  using the models of Cervino 1998). Mac Low & Ferrara (1999) have suggested that for galaxies with masses comparable with that of IZw 18, such an energy is likely to eject out of the galaxy all the metals formed by massive stars. If true, it means that bursts are unlikely to enrich the ISM by much! We thus have investigated the effect of the loss of newly synthesized elements by galactic winds. As a less extreme hypothesis, we assumed that only a fraction of the SN ejecta (and not the totality) leaves the galaxy.

#### 3.2. The effect of metal loss

The possibility that the energy released by the SN could eject their products out of the galaxy was proposed earlier by Russell et al. (1988). However, intermediate mass stars, evolving more slowly, will eject their metals after the SN explosion of the most massive stars. Since the kinetic energy released, mainly in stellar winds, is lower than for the massive stars, their metal products should be retained. This will result in a low effective



**Fig. 1.** Time evolution of the gas fraction, oxygen and carbon abundances for recurrent bursts with a Salpeter IMF, duration of 20 Myr and  $\text{SFR}=0.065 M_{\odot}/\text{yr}$ . The dots represent the measured abundances.



**Fig. 2.** Colors evolution (U-B, B-V, V-K) for recurrent bursts with a Salpeter IMF, duration of 20 Myr and  $\text{SFR}=0.065 M_{\odot}/\text{yr}$ . The plots include the additional 0.1 uncertainty (from the comparison between the models) with the observational errors to define a region (between dashed lines) of compatibility between the model and the observations. The solid lines represent the prediction of the model. If the solid line goes into the region between dashed lines, it means that the model does reproduce the observations within the error bars.

enrichment in oxygen (main product of massive stars), but in a relatively normal enrichment in carbon (mostly produced in intermediate mass stars). This hypothesis of “differential galactic wind” seems to be necessary to reproduce the abundance measurements in some but not all the galaxies (Marconi et al. 1994; Tosi 1998).

If a fraction of metals escapes from the galaxy during a burst, the number of bursts necessary to reach the observed abundance in IZw 18 will be larger. We thus ran a model in which 80% of the metals produced by stars more massive than  $9 M_{\odot}$  left the galaxy and did not contribute to its chemical enrichment. Assuming the same parameters for the bursts as previously, five bursts were necessary to reach the oxygen abundance level seen in IZw 18. We thus assumed recurrent bursts occurring every 3 Gyr. The results of this model are shown in Figs. 1 and 2.

Fig. 1 shows that if the oxygen abundance is reproduced after 5 bursts, the differential winds hypothesis results in an overproduction of carbon. Moreover, if the carbon abundance in IZw 18 is lower than the measurements of Garnett et al. (1997),

as suggested by Izotov & Thuan (1999), the discrepancy is even larger and completely rules out this model. However, the uncertainties on the yields remain large (see for example Prantzos 1998, 1999). For example, the detection of WR in IZw 18 (Legrand et al. 1997) can imply that the mass loss rate of massive stars are twice the standard ones and the metals produced by the intermediate mass stars may also leave the galaxy. We thus think that this argument alone is not strong enough to invalidate definitively this scenario.

On the other hand, Fig. 2 shows that after four bursts, the expected colors (essentially V-K) do not correspond with those observed. This is due to the fact that the old population remaining from the previous star formation events contributes more and more and reddens the colors. This constraint is strong, since it is difficult to ignore old population. Of course, the constraint from the observed colors is not really the number of previous bursts (because it depends on their strength) but the ratio of young stars (formed in the current burst) versus old stars (remaining from all the previous star formation events). We thus ran another model with recurrent bursts of intensity comparable to the current one (Mas-Hesse & Kunth 1999) every 1.5 Gyr. This model shows, like in Fig. 2, that the observed colors become incompatible with observations after 6 of these bursts. It thus appears that the total mass of stars ever formed previously to the current burst cannot be larger than 6 times the total mass of stars involved in the current burst. Only 2 or 3 of these bursts produce enough metals to account for the observed abundances (if all the metals remain into the galaxy). Thus if the present day metallicity results from previous star formation events *with mass loss*, this constrains the fraction of metals lost by the galaxy to be lower than 50-70%. For the same reason, this rules out models inferring a large number of bursts in which most of the metals leave the galaxy or produce a hot metal-rich halo as suggested by Pantelaki & Clayton (1987).

### 3.3. A continuous low star formation rate

As discussed by Legrand et al. (1999), metals observed in IZw 18, and also in other starbursts galaxies, result from a previous star formation episode. Assuming that the present burst in IZw 18 is the first one, we evaluated the continuous star formation rate required to reproduce the observed **oxygen** abundance after 14 Gyr. In this scenario, a mild star formation process would have started a long time ago but the galaxy would presently undergo its first strong starburst event. We found that a SFR of only  $10^{-4} g M_{\odot} \text{yr}^{-1}$  (i.e.,  $10^{-3} g M_{\odot} \text{Gyr}^{-1}$  by unity of mass of gas in the galaxy), where  $g$  is the fraction of gas (in mass) available, can reproduce the observed oxygen abundance in IZw 18. Moreover, this model reproduces perfectly the carbon abundance measured by Garnett et al. (1997). The kinetic energy injection rate, evaluated using the models of Cervino (1998), is for this scenario of  $9 \cdot 10^{36} \text{ erg s}^{-1}$ , i.e., probably insufficient to eject the metals out of the galaxy (Mac Low & Ferrara 1999; Silich & Tenorio-Tagle 1998).

Moreover, the kinetic energy is not deposited in one single region like in a burst, but as the continuous star formation

is supposed to occur sporadically in location, the injected energy is diluted over the whole galaxy, reducing the efficiency of ejection of the metals (see also Strickland & Stevens 1999). For these reasons, we assumed that all the metals produced by the continuous star formation rate are retained in the galaxy. Of course, this continuous star formation regime represent an extreme case. We cannot rule out the existence of intermediate models in which the star formation history would be a succession of very small bursts without or with very low metal loss. However, these models will appear, in average, as a rather continuous star formation rate. The motivation for preferring a continuous star formation rate is principally the absence of observational evidences for gas rich galaxies with a SFR equal to zero, even among LSBG.

Finally, in order to compare the colors predicted by the model, we added the present burst at 14 Gyr. The characteristics for the current burst, *i.e.*, a SFR of  $0.023 M_{\odot} \text{ yr}^{-1}$  during 20 Myrs, were taken from Mas-Hesse & Kunth (1999). The evolution with time of the gas fraction, oxygen and carbon abundances is presented in Fig. 3, whereas the evolution of the colors is shown in Fig. 4.

Note that the observations of Thuan (1983) were done using a  $8''$  circular aperture, which is smaller than IZw 18. Thus the total asymptotic magnitudes may be smaller than the ones measured by Thuan (1983). Doublier (1998) has shown that this difference can be as large as 3 magnitudes, due to the presence of an old underlying stellar population. However, as IZw 18 is a very unevolved object, the old underlying population must be very faint. We have evaluated the difference between the observations of Thuan (1983) and the total magnitude expected from our model in the case of the existence of an old underlying population, due to continuous star formation, extending uniformly over the whole galaxy. We assumed that the old underlying population extends over  $60'' \times 45''$  as discussed later. If  $m$  is the total magnitude emitted in a band, it can be written as

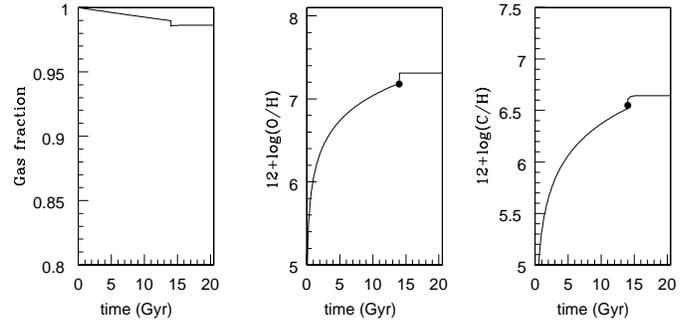
$$m = -2.5 \text{Log}(E_b + E_{\text{ci8}} + E_{\text{co8}}) \quad (2)$$

with  $E_b$  the flux emitted by the burst (localized in the central region included in the measurement of Thuan 1983),  $E_{\text{ci8}}$  and  $E_{\text{co8}}$  the fluxes emitted by the old underlying stellar population inside and outside the  $8''$  aperture, respectively. The magnitude measured by Thuan (1983) are then:

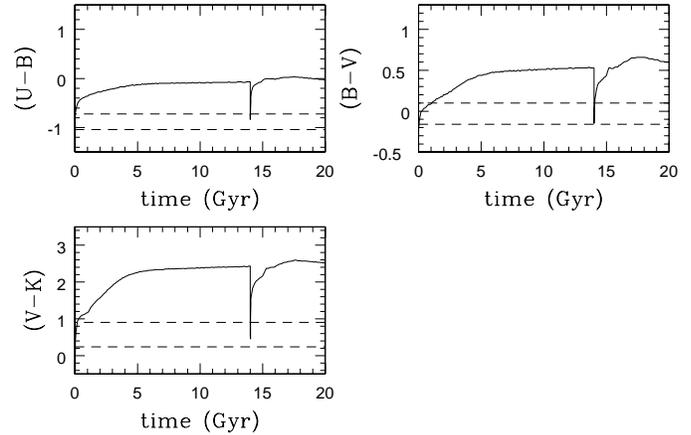
$$m_8 = -2.5 \text{Log}(E_b + E_{\text{ci8}}) \quad (3)$$

$E_{\text{co8}}$  can be evaluated using the flux of the old underlying stellar population predicted by the model. Under these assumptions, the magnitude measured by Thuan (1983) should be decreased by 0.20 in J and 0.24 in K. Thus this does not change the main results and the model predicts colors consistent with the observations.

The fraction of gas consumed remains very low; thus  $g$  is always close to 1. This means that the SFR is rather constant. The model is thus fully compatible with all the observations within the error bars.



**Fig. 3.** Time evolution of the gas fraction, oxygen and carbon abundances for the continuous SFR model with a Salpeter IMF. The dots represent the measured abundances.



**Fig. 4.** Colors evolution (U-B, B-V, V-K) for the continuous SFR model with a Salpeter IMF. The dashed lines delimit the zone of compatibility between the model and the observations.

### 3.4. First consequences

If we suppose that the continuous star formation occurs sporadically over the whole galaxy like in LSBG (Van Zee et al. 1997c), the observed homogeneity of abundances (within the NW region and also between NW and SE regions of IZw 18) is a natural consequence of this scenario. The uniformly distributed star formation and the long time evolution (14 Gyr) ensure the dispersal and homogenizing of the metals over the whole galaxy.

We evaluated the number of stars with a mass greater than  $8 M_{\odot}$ , formed over 14 Gyr, to be around 12000. This corresponds to 120 massive stars (typically an open cluster) formed every 140 Myr. Taking their lifetime into account, we expect to see around 13 stars with mass greater than  $8 M_{\odot}$  at a given epoch. We also evaluated the SN rate expected to be  $7.5 \cdot 10^{-7} \text{ yr}^{-1}$ , or relatively to the mass of gas, around  $10^{-14} \text{ yr}^{-1} \cdot M_{\odot}^{-1}$ . This can be compared to the SN rate in our galaxy which amount  $10^{-13} \text{ yr}^{-1} M_{\odot}^{-1}$  (Tammann et al. 1994).

### 3.5. Threshold and efficiency of star formation

There is a relationship between the star formation rate and the gas surface density (Schmidt 1959). A simple power law de-

scribes this link at “high” density, but this relationship breaks down under a critical threshold (Kennicutt 1989, 1998). The existence of a gas density critical threshold under which star formation would be inhibited had been proposed by Quirk (1972). This threshold would be associated with large scale gravitational instabilities for formation of massive clouds. In a thin isothermal disk, the critical gas surface density threshold (Toomre 1964; Cowie 1981) is (Kennicutt 1989):

$$\Sigma_c = \alpha \frac{\kappa c}{3.36G} \quad (4)$$

with

$$\kappa = 1.41 \frac{V}{R} \left(1 + \frac{R}{V} \frac{dV}{dR}\right)^{1/2} \quad (5)$$

where  $c$  is the dispersion velocity in the gas,  $\kappa$  is the epicyclic frequency (derived from the rotation curve), and  $V$  the rotation velocity at the distance  $R$  from the center of the galaxy. However, Van Zee et al. (1997c) have shown that despite a gas density lower than the threshold, LSBG are undergoing star formation. We suggest that in low density objects, the density can fluctuate locally and get above the threshold in some places. This could induce localized and faint star formation (Van Zee et al. 1997c; Skillman 1999). For IZw 18, observations of Van Zee et al. (1998) and Petrosian et al. (1997) reveal a solid body rotation (in the central part) with parameter  $\frac{dV}{dR} = 70 \text{ km s}^{-1} \text{ kpc}^{-1}$ . Using a dispersion velocity in the gas of  $12 \text{ km s}^{-1}$  (Van Zee et al. 1998), the critical threshold is of the order of  $1.5 \cdot 10^{22} \text{ atoms cm}^{-2}$ . On the other hand, Van Zee et al. (1998) have shown that the abundances in the HI halo are comparable to the one in the HII region. This suggests that star formation may have also occurred quite far away from the central regions. This is reinforced by the observation of star formation in regions with density lower than the threshold (Van Zee et al. 1997c). As most of the HI gas responsible of the absorption measured by Kunth et al. (1994) is concentrated at density higher than  $10^{20} \text{ atoms cm}^{-2}$ , we assumed that this level represent the density limit for the continuous star formation. This appears as a lower limit because metal produced by star formation in more inner regions can also have been dispersed and mixed at larger distances. This implies that local fluctuations in the density should be up to a factor of 150 and that the continuous SFR could occur over a surface of  $60 \times 45''$  (Van Zee et al. 1998).

The continuous star formation rate evaluated is very low. From the work of Wyse & Silk (1989), we can compute the star formation efficiency of such a process. According to these authors, the star formation rate at a distance  $r$  of the center and a time  $t$  is:

$$\psi(r, t) = \epsilon \cdot \Omega(r) \cdot \mu_{HI}(r, t) \quad (6)$$

where  $\epsilon$  is the star formation efficiency,  $\Omega(r)$  the local angular frequency and  $\mu_{HI}(r, t)$  the surface density in HI. Using the rotation curves computed by Van Zee et al. (1998) and Petrosian et al. (1997), we found that  $\Omega = (8.76 \cdot 10^7 \text{ yr})^{-1}$ . The HI mass measured by Van Zee et al. (1998) using a surface of

$2.3 \times 3 \text{ kpc}$  gives a mean surface density of  $3 M_{\odot} \text{ pc}^{-2}$ . The star formation rate is then  $\psi = 0.18 \epsilon M_{\odot} \text{ yr}^{-1}$ , which compared with the results of our model ( $10^{-4} M_{\odot} \text{ yr}^{-1}$ ), leads to a very low star formation efficiency of  $\epsilon \sim 6 \cdot 10^{-4}$ .

#### 4. Generalization of the continuous star formation hypothesis

##### 4.1. Underlying population and faint objects population

If the starburst in IZw 18 is the first one in its history, we can expect that objects which have not yet undergone a burst (but only a continuous star formation rate) do exist. They should then look like IZw 18 just before the present burst. Our modeling predicts that after 14 Gyr of continuous star formation, the magnitude of a IZw 18-like object is of the order of 20 in V and 17.5 in K. These magnitudes represent the brightness of the old underlying stellar population in IZw 18. Assuming that the continuous star formation occurred in regions where the HI column density was greater than  $10^{20} \text{ cm}^{-2}$ , *i.e.*,  $60 \times 45''$  (Van Zee et al. 1998), the expected surface brightness would be of the order of  $28 \text{ mag arcsec}^{-2}$  in V and  $26 \text{ mag arcsec}^{-2}$  in K. These values are an upper limit (in  $\text{mag arcsec}^{-2}$ ); if a fraction of metals is ejected out of the galaxy, the SFR needed to produce the observed abundances will be higher and the total luminosity and surface brightness will be increased. Moreover, as discussed in Sect. 3.5, the density limit adopted for the continuous SFR is a lower limit and the region where the continuous SFR can occur may be smaller, resulting in higher surface brightness. However, the extreme faintness of the old underlying population probably explains why no strong evidence for its existence has been found in IZw 18 (Thuan 1983; Hunter & Thronson 1995) until recently when reanalyzing HST archive images Aloisi et al. (1999) found stars older than 1 Gyr. In all the cases, these very low surface brightness levels will be reachable with 8m class telescopes like the VLT and Gemini for rather closeby objects. A search for a faint old underlying population, in the external part of dwarf galaxies like IZw 18, resulting from a continuous star formation process, is planned. If successful, this will support the existence of a class of very low surface brightness galaxies, which never underwent a burst, but evolved through a continuous weak star formation rate.

##### 4.2. LSBG as quiescent counterparts of starbursts

We also studied the state of dwarf galaxies between bursts. IZw 18 appears as an extreme object which could present for the first time a strong star formation event. The chemical abundance levels in most of the starbursts galaxies suggest that they have undergone at least two or three previous bursts. Using the model described below, we investigated the simple following star formation history for a dwarf galaxy with mass, size and distance comparable to IZw 18:

- A continuous star formation rate since 14 Gyr.
- Two bursts with a SFR of  $0.065 M_{\odot} \text{ yr}^{-1}$  and a duration of 20 Myr, respectively at 8 and 11 Gyr.

The absolute magnitudes predicted are around -10 and the surface brightness about 25 mag arcsec<sup>-2</sup> in B. These values correspond to objects at the extreme end of the luminosity function of the galaxies as observed by Lo et al. (1993).

We have also compared the continuous SFR required for IZw 18 ( $10^{-4} M_{\odot} yr^{-1}$ ) with those measured by Van Zee et al. (1997a,b,c) in low surface brightness galaxies. As these objects have different sizes and masses, we normalized the SFR to the total HI mass. For IZw 18, the HI mass lies between  $2.6 \cdot 10^7 M_{\odot}$  (Lequeux & Viallefond 1980; Van Zee et al. 1998, for the main body) and  $6.9 \cdot 10^7 M_{\odot}$  (Van Zee et al. 1998, for the whole galaxy, including the diffuse low column density component). The comparison is shown in Table 1. It appears that the continuous SFR as predicted by our scenario is comparable, relative to the HI mass, to the lowest SFR observed in quiescent and low surface brightness galaxies (like for example in UGC8024 or UGC9218).

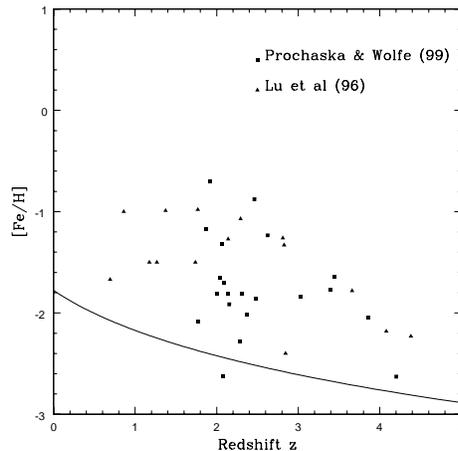
We then conclude that LSBG and quiescent dwarfs are likely to be the quiescent counterparts of starburst galaxies.

#### 4.3. Generalization to all galaxies

If a continuous star formation rate exists in IZw 18, it must exist in other dwarf galaxies, and may be, in all galaxies. There are some hints for such a hypothesis.

For example, the extreme outerparts of spirals, where no strong star formation event occurred and where the metals formed in the more active inner zones have not diffused, must have low abundances and low surface brightness. For example, let us assume that the bulk of “strong” star formation occurs in a spiral galaxy at distances less than the optical radius ( $\sim 10$  kpc). Roy & Kunth (1995) have shown that metals can be dispersed at scales up to 10 kpc in about 1 Gyr, so extending their results we can expect that if recent (less than 1 Gyr ago) star formation occurred in external regions located at 10 kpc from the center (one optical radius), the newly formed metals could affect abundances at distances up to 20 kpc from the center in few Gyrs. If this star formation is relatively recent, we expect that the most external region of the disk (more than 2-3 optical radii) will not be affected by “strong” star formation events their metallicity will be solely the result of the “underlying” low continuous star formation rate. Extrapolations of metallicity gradients in spiral galaxies lead to abundances comparable to that of IZw 18 at radial distances of about three optical radii (Ferguson et al. 1998; Henry & Worthey 1999). This corresponds to the size of the halos or disks susceptible to give rise to metallic absorption in quasar spectra (Bergeron & Boisse 1991).

We showed that a continuous low star formation rate results in a steady increase of the metallicity of the interstellar gas. We have compared the evolution of the iron abundance predicted from our model with the measurements in DLA systems in Fig. 5. The abundances predicted by the model mimic the lower envelope of these measurements. If we assume that these absorption systems are associated with galaxy halos (Lanzetta et al. 1995; Tripp et al. 1997), this indicates that such a process can account for a minimal en-



**Fig. 5.** Comparison of the predicted and observed evolution with redshift of the abundance [Fe/H]. The points represent the data from Lu et al. (1996) and Prochaska & Wolfe (1999) and the solid line the model prediction for a constant star formation rate.

richment of the ISM. One measurement appears lower than the model prediction. However, Fe atoms are likely to condensate into grains (Lu et al. 1998; Pettini et al. 1997), so the iron abundance measurements are only lower limits of the real iron abundances. Moreover Bergeron & Boisse (1991) have shown that absorptions should occur at distances of up to 4 Holmberg radius. These regions are likely to present very low density, and may be too under-critical to allow star formation, even in the low SFR regime described here. Moreover, the partial ionization of these regions by the diffuse ionizing background (Van Gorkom 1991; Corbelli et al. 1989; Maloney 1990; Corbelli & Salpeter 1993a,b) will also contribute to prevent star formation. Their metallicity could thus be due only to metals which have diffused from the inner regions. If true, we can expect, in these regions, abundances lower than what is predicted from the continuous SFR.

## 5. Conclusion

We have investigated different star formation histories for IZw 18 using a spectrophotometric model coupled with a chemical evolution model of galaxies. We have shown that if the observed metallicity results only from burst events with galactic winds, no more than 50-70% of the newly synthesized metals may have been ejected out of the galaxy. This is because a larger metal loss rate will require to form more stars to reach the measured abundances, hence resulting in redder colors than what is observed, due to an overproduction of old underlying low mass stars. Following the suggestion of Legrand et al. (1999), we investigated the hypothesis of a low, but continuous, SFR which should account alone for the observed metallicity in IZw 18. We have shown that the metals in IZw 18 are likely to result from a mild continuous star formation rate which took place independently from bursts. This star formation would be due to local fluctuations in the density which exceeds sporadically the threshold for star formation. Using a spectrophotometric model and a chemical evolution model of galaxies, we demonstrated

that a continuous star formation rate as low as  $10^{-4} M_{\odot}/yr$  occurring for 14 Gyrs can reproduce all the main parameters of IZw 18. The generalization of this model to all galaxies accounts for many observed facts, such as the presence of star formation in quiescent dwarfs and LSBG, the increase with time of the metallicity of the most underabundant DLA systems, the extrapolation of metallicity in the outerparts of spiral galaxies, the lack of galaxies with a metallicity lower than IZw 18, the apparent absence of HI clouds without optical counterparts, and the homogeneity of abundances in dwarfs galaxies. Moreover, we predict for IZw 18 and other extremely unevolved galaxies, the presence of an old underlying stellar population (resulting from this continuous star formation process) at a surface brightness level of at least 28 mag arcsec<sup>2</sup> in V and 26 mag arcsec<sup>2</sup> in K. Finally, we have shown that the parameters for the low continuous star formation rate are comparable to what is observed in LSBG and quiescent dwarfs, suggesting that these objects could be the quiescent counterparts of starburst galaxies.

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