Star Formation in Dwarf Galaxies

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ABSTRACT

We explore mechanisms for the regulation of star formation in dwarf galaxies. We concentrate primarily on a sample in the Virgo cluster, which has HI and blue total photometry, for which we collected Hα data at the Wise Observatory. We find that dwarf galaxies do not show the tight correlation of the surface brightness of Hα (a star formation indicator) with the HI surface density, or with the ratio of this density to a dynamical timescale, as found for large disk or starburst galaxies. On the other hand, we find the strongest correlation to be with the average blue surface brightness, indicating the presence of a mechanism regulating the star formation by the older (up to 1 Gyr) stellar population if present, or by the stellar population already formed in the present burst.

Subject headings: galaxies: irregular -galaxies: stellar content - HII regions - stars: formation

1. Introduction

The star formation (SF) is a fundamental process in the evolution of galaxies and is far from being well understood. The SF is usually characterized by the initial mass function (IMF) and the total SF rate (SFR), which depends on many factors such as the density of the interstellar gas, its morphology, its metallicity, *etc.* According to Larson (1986), four major factors drive star formation in galaxies: large scale gravitational instabilities, cloud compression by density waves, compression in a rotating galactic disk due to shear forces, and random cloud collisions. In galaxies with previous stellar generations additional SF triggers exist, such as shock waves from stellar winds and supernova explosions. In dense environments, such as clusters of galaxies and compact groups, tidal interactions, collisions with other galaxies, ISM stripping, and cooling flow accretion probably play some role in triggering the SF process. The triggering mechanisms were reviewed recently by Elmegreen (1998).

While "global" phenomena, such as the first two SF triggers of Larson (1987), play a large part in grand design spirals, random collisions of interstellar clouds may provide the best explanation for dwarf galaxies with bursts of SF. Due to their small size, lack of strong spiral pattern, and sometimes solid-body rotation (*e.g.,* Martimbeau *et al.* 1994, Blok & McGaugh 1997), the star formation in dwarf galaxies is not triggered by compression due to gravitational density waves or by disk shear. Therefore, understanding SF in dwarf galaxies should be simpler than in other types of galaxies.

The characterization of the SF processes by a star formation rate (SFR) controlled by the interstellar gas density as a power law was first introduced by Schmidt (1959). The volume density of young stars, ρ_*, is related to the volume density of HI gas in the Galactic disk as $\rho_* = a\ \rho_{gas}^n$, where n is a constant, probably $\approx$2 for spiral galaxies. In other galaxies the convention is to express the quantities as projected densities of stars (Σ_*) and of gas, as actually observed: $\Sigma_* = A\ \Sigma_{gas}^n$. This is usually studied by correlating the surface density of a young star tracer, such as the Hα surface brightness, with the gas column density.

The Hα emission from a galaxy measures its ongoing SFR (Kennicutt 1983). Gallagher *et al.* (1984) derived an analytic relation between the detected Hα flux and the present SFR of a galaxy; similar relations were derived by Kennicutt *et al.* (1994). The blue luminosity of a galaxy, on the other hand, measures its past star formation integrated over the last $\sim 10^9$ yrs (Gallagher *et al.* 1984). The newly formed stars, of which the more massive produce the Lyman continuum photons which ionize hydrogen and produce the Hα emission, contribute also to the blue light output of a galaxy. This contribution is minor in comparison to that from the stars already existing in a galaxy, unless the SF event is the first in the history of the galaxy or the star burst is unusually strong. Interestingly, Tresse & Maddox (1998) found recently that the Hα luminosity of a galaxy correlates with its blue absolute magnitude.

Kennicutt (1998) found that his parametrization of the Schmidt law fitted well the SF pattern of spiral and IR-selected starburst galaxies. An alternative to the Schmidt law, proposed by Silk (1997), fitted equally well. In this variant, the SFR per unit area scales with the ratio of the gas surface density to the local dynamical timescale: $\Sigma_{SFR} \propto \frac{\Sigma_{gas}}{\tau_{dyn}} \propto \Sigma_{gas} \times \Omega_{gas}$, where Ω_{gas} is the angular rotation speed and the scenario fits disk configurations. Kennicutt (1998) adopted $\Omega_{gas} = \frac{V(R)}{R}$, where V(R) is the rotation velocity of the gas at a distance R.

Hunter *et al.* (1998) tested a set of SF predictors on two small samples of dwarf galaxies, one measured by them and another derived from de Blok (1997). They found that the ratio of Σ_{gas} to the critical density for the appearance of ring instabilities did not correlate with the star formation, but that the stellar surface brightness did. From this, they concluded that possibly the stellar energy input provides the feedback mechanism for star formation.

We concentrate on a sample of late-type dwarf galaxies in the Virgo cluster (VC). The reason for selecting dwarfs was to limit the number of possible trigger mechanisms of SF; these objects are devoid of large-scale SF triggers, as explained above. Having only VC members limits the sample to a well-defined galaxy background; in addition, all objects are at ∼the same distance and have HI information from the same source. We tested for correlations between the Hα emission and other observed quantities, in order to investigate mechanisms which regulate SF in dwarf galaxies. The justification to correlate the Hα SFR index against Σ_{gas} is the finding of Kennicutt (1998) that a Schmidt-type law seems to fit large galaxies. If the SFR depends on the gas density ratioed to the dynamical timescale (Silk 1997, Kennicutt 1998), a correlation with $\Sigma_{gas} \times \Omega_{gas}$ is expected. Finally, if the SFR depends on the local population of blue stars, as found by Hunter *et al.* (1998), then a dependence on the average blue surface brightness is expected. We also tested the SFR against the ISM gas velocity, represented by the width of the HI line profile at 20% of its peak intensity (σ(HI)), and against a combination of it and the surface density of HI, in a manner similar to that suggested by Silk (1997).

2. The sample

Our sample consists of 52 late-type dwarf galaxies in the VC selected from Binggeli *et al.* (1985, VCC), with HI measurements from Hoffman *et al.* (1987, 1989). The sample was constructed in order to enable the detection of weak dependencies of the star formation properties on hydrogen content and surface brightness. We selected two sub-samples by surface brightness; one represents a high surface brightness (HSB) group and is either BCD or anything+BCD, and another represents a low surface brightness (LSB) sample and includes only ImIV or ImV galaxies. The morphological classification, which bins the dwarf galaxies in the HSB or LSB groups, is exclusively from the VCC. In addition, the galaxies are binned by their HI flux integral (FI) from Hoffman *et al.* (1987, 1989). The HSB sub-sample was selected with galaxies of high HI content (FI>1500 mJy km s^{-1}) or with low HI content (0<FI<600 mJy km s^{-1}) and is described in Almoznino & Brosch (1998, AB98). The LSB sub-sample has FI>1000 for the high HI sample or 0<FI<700 mJy km s^{-1} for the low HI sample (described in Heller *et al.* 1998, HAB98). The LSB sub-sample is complete, in the sense that it contains all objects classified ImIV or ImV in the VCC with m_B <17.2 mag. The HSB sub-sample contains 45% of the VCC galaxies of this type with m_B <17.2. Although not complete, it is representative of this type of object in the VC.

The galaxies were observed at the Wise Observatory (WO) in Mizpe-Ramon from 1990 to 1997, with CCD imaging through the B, V, R, and I broad bands, and narrow Hα bandpasses in the rest frame of each galaxy. The discussion of all observations and their interpretation is the subject of other papers (AB98, HAB98). We restrict the discussion here to the analysis of the integrated Hα flux F(Hα), as it reflects on the global process of SF. In particular, we concentrate on correlations of this SFR index with other parameters collected from the literature.

We compare our results with other dwarf galaxies for which we collected published data. We selected Case galaxies from Salzer *et al.* (1995, S95) of types HIIH, DHIIH, BCD, MagIrr, and GIrr, as most similar to our VC sample. We further required that HI observations would exist for the Case galaxies, and collected seven such objects. As these galaxies do not have total Hα fluxes listed, we estimated those from (a) the total blue magnitude m_B, (b) the listed equivalent width of the Hβ line, and (c) by assuming $\frac{H\alpha}{H\beta}$=2.9 (Case B, with no extinction). A second comparison sample of eight galaxies originates from Martin (1997), where each object has an average Hα surface brightness measure in the 1" wide slit. FI and σ(HI) values were collected from Huchtmeier & Richter (1989), while total blue magnitudes and sizes originate from NED. No corrections for Galactic or internal extinction were applied to the data. We also assumed that the Balmer emission observed spectroscopically is representative of the entire galaxy.

We prefer to use here distance-independent measures, which are not sensitive to the exact location of a galaxy in the VC, to the value of H_0, or to deviations from a smooth Hubble flow, and to stick, as much as possible, to directly observable quantities. The observables F(Hα), FI, and m_B have, therefore, been normalized to the optical area of each galaxy, yielding "surface brightness" measures per square arcmin. We calculated average blue surface magnitudes Σ(B), average HI flux integrals per unit surface Σ(HI), and average Hα surface brightnesses Σ(Hα) for all objects. The optical area of a galaxy is defined here as A=$\frac{\pi D^2}{4R}$, with D the major axis in arcmin and R the axial ratio listed in VCC or estimated from the image of the object on the Digitized Sky Survey, to yield Σ(HI).

We used in some correlations σ(HI), and derived $\Omega = \frac{\sigma(HI)}{D}$ as a representative gas dynamical property at the outermost optical radius. This definition of Ω is not purely equivalent to that used by Kennicutt (1998), but it does not require cosmological assumption in its derivation. We caution at this point that Σ(HI) may overestimate the surface density of HI in cases where the hydrogen distribution extends beyond the opical area of an object. Cases where the HI distribution was 3$\times$ and more larger than the optical size of a galaxy were reported by Taylor *et al.* (1995). However, while very extended HI distributions do exist, they are not a general characteristic of dwarf galaxies. Hoffman (private communication) found that only two of the five Virgo cluster BCDs mapped at Arecibo showed evidence for being extended. In most cases, the Arecibo beam will cover more than 3$\times$ the optical size of one of our objects, implying that not much HI could have been missed in the measurements we use here. In absence of synthesis or multi-beam mapping of the HI distributions, we selected to use the coarse measure of Σ(HI) as defined here, with all caveats mentioned.

The WO sample ranges over more than two orders of magnitude in Σ(HI), over more than three orders of magnitude in Σ(Hα), and over slightly less that two orders of magnitude in Σ(B). The comparison sample from Salzer *et al.* (1995) is more restricted in the range of Hα, while the galaxies from Martin (1997) have more intense Hα than the WO objects. In general, galaxies from Salzer *et al.* are $\sim 2\times$ more distant than the VC sample, while objects from Martin are $\sim 3\times$ closer than the VC.

3. Star formation correlations

We checked first correlations between global parameters of our dwarf galaxy sample, such as total blue brightness, total HI content, *etc.* In all correlations we considered only detected quantities (no upper limits were included). We did not find that m_B and the HI FIs were correlated in any of the subsamples (for the entire WO sample the correlation coefficient was 0.57, F=17.4). This scatterplot is shown in the top left panel of Figure 1. Note that some degree of correlation would be expected only from the distance effect, with both m_B and FI being lower for more distant objects.

The plot of Σ(B) vs. Σ(HI), shown in the top right panel of Fig. 1, indicates that galaxies with more HI per unit area tend also to have higher blue surface brightness, *i.e.,* a higher past-averaged SFR, but this correlation was not very significant. We found that logΣ(Hα) correlates with the HI line width (correlation coefficient 0.61, F=21.3) and show this in the left middle panel of Fig. 1. Dwarf galaxies with brighter blue surface brightness tend also to have wider HI profiles (correlation coefficient 0.51, F=13.6), as the right middle panel of Fig. 1 shows. Σ(HI) correlates also weakly with σ(HI). This is illustrated in the lower left panel of Fig. 1.

Kennicutt (1998) showed that in a sample of large spirals and starburst galaxies the average Hα disk surface brightness correlates well with the average molecular and atomic gas surface density. Dwarf galaxies have very small quantities of molecular gas (*e.g.,* Gondhalekar *et al.* 1998), therefore using here $\Sigma(HI)$ should represent well the total ISM. This correlation, shown in the lower right panel of Fig. 1, was also weak, and the combined WO sample had a correlation coefficient of only 0.52 (F=13.1)

A better correlation was found for Σ(Hα) *vs.* the "Silk"-type parameter Σ(HI)Ω. Figure 2 shows this for the two VC samples (HSB=filled diamonds, LSB=squares), as well as for the comparison samples from Salzer *et al.* (1995; triangles) and Martin (1997; filled circles). Note that the two VC samples join up nicely, with the HSB galaxies being brighter and more Hα-intense than the LSB objects. The correlation coefficient for the combined WO sample is 0.70 (F=34.2) and the slope is 0.93±0.16. The logΣ(Hα) correlates even better with the blue surface magnitude, as Figure 3 shows. For the combined WO sample the correlation coefficient is 0.77 and the slope is –0.63±0.09 (F=51.2).

The Salzer *et al.* (1995) and the Martin (1997) galaxies deviate in both plots from the trend set by the VC sample. Some of the discrepancy may be the result of our samples being measured in a uniform and consistent manner, whereas the plotted parameters for the comparison samples were calculated from published data and some assumptions (explained above). The Martin galaxies appear consistently above the location of the WO galaxies; it is probable that their total Hα flux was over-estimated by assuming that the slit average is representative of the entire galaxy. This is confirmed for the three objects in common with Marlowe *et al.* (1997), which have consistently lower total Hα fluxes than adopted by us here. The Salzer *et al.* (1995) objects are generally below the WO objects. They have significant extinction ($< c_\beta > \approx 0.77$), which translates into an under-estimate of the Hα emission when scaling from the Hβ flux. In addition, the Hβ fluxes were not corrected for underlying absorption; this also causes an Hα under-estimate. Other reasons for discrepancies may be the different distances to the two comparison samples, which influence Ω we use here through the angular diameter of a galaxy, used in the present derivation.

4. Discussion

We mentioned above a number of triggers of star formation. Some, such as shear and two-fluid instabilities, or spiral density waves, are important mainly in large disk galaxies and thus are not relevant for dwarfs. The sample studied here is comprised of fairly isolated galaxies, although this was not a selection criterion. The galaxies are distant enough from other objects to discount recent (few 10^7 yrs) interactions as possible star formation triggers. In these dwarfs the expectation is that the SF may be regulated only by the gas density, or by the gas density combined with some factor connected with the stellar content of the galaxy. We checked here various correlations of the star formation indicator Σ(Hα) with global or specific (per unit area) galaxy parameters. The "expected" correlations, observed by Kennicutt (1998) to fit well spiral galaxies, were found to be much weaker in dwarfs. The strongest correlation was with Σ(B), while the local ISM dynamic indicator Σ(HI)Ω showed the second strongest correlation.

The correlation found for the CFRS survey galaxies ($<z>\simeq 0.2$, Tresse & Maddox 1998), between the global M_B and log L(Hα), can be understood if that survey selected preferentially galaxies of similar sizes in blue and in hydrogen emission, reducing the problem to a correlation between area-normalized quantities. These galaxies are much brighter ($M_B \geq -21$ mag) than the dwarfs discussed here and, being selected on the basis of their I-band emission, are probably not representative of the "star-forming dwarfs" class.

Our findings support a scenario whereby the star formation is not controlled by the gas volume density, by its surface density, or by the ratio of the gas surface density to a local dynamical timescale. The strongest correlation, based on the correlation coefficient and the value of the F-statistic, was with the average blue surface magnitude, as found also by Hunter *et al.* (1998). There the question was posed whether this was an effect of the SFR being ∼constant over the last ∼1 Gyr. We can definitely rule out this possibility, as at least one of our objects (VCC 144; Brosch *et al.* 1998) seems to exhibit its first SF burst. Many other galaxies, mainly from the LSB sample, show a number of small HII regions indicating localized star formation at present. The colors (AB98) are best fitted by (at least) two stellar populations formed in short bursts, spaced a few 100 Mys to 1 Gyr apart. This indicates that a constant SF is not a serious possibility for the dwarf galaxies studied here.

5. Conclusions

We tested correlations among parameters related to star formation, gas and stellar content, and internal dynamics on a sample of dwarf galaxies in the Virgo cluster. We found that both the Schmidt law and the more recent relation derived by Silk (1997) do not fit these galaxies as well as they do spirals (Kennicutt 1998). The strongest correlation of the Hα surface brightness, which measures the present star formation strength, was with the average blue surface brightness, supporting the proposition of Hunter *et al.* (1998) that a feedback mechanism must be at work to regulate the present SF by the older stellar population.

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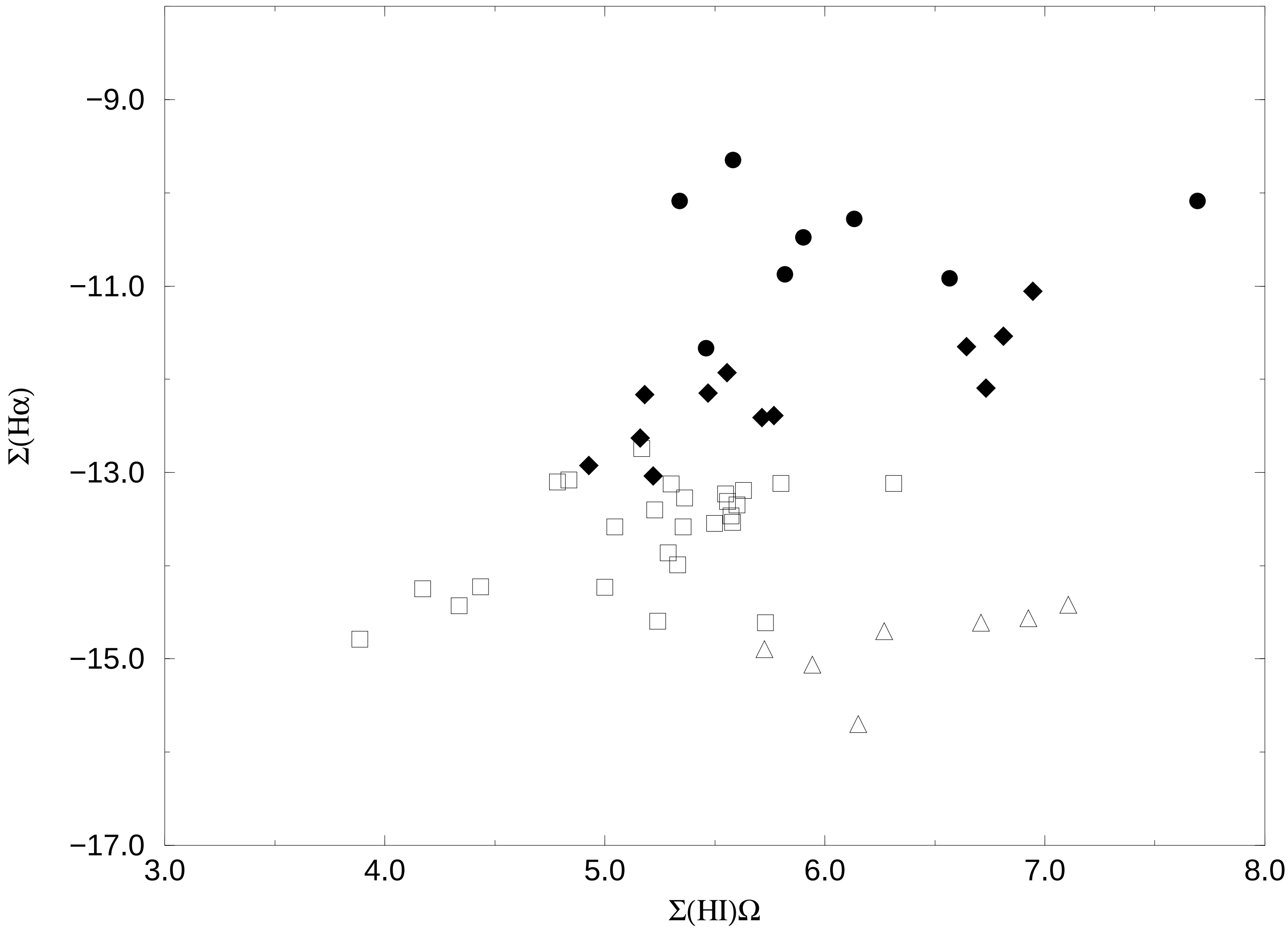
Figure captions

Figure 1: Scatterplots for various observables measured or calculated for the Virgo cluster sample of dwarf irregular galaxies. The figure shows the total HI flux integral *vs.* the total blue magnitude in the top left panel, the logarithm of the HI surface flux integral (HISFI) *vs.* the blue surface magnitude in the top right panel, the logarithm of the Hα surface brightness (Σ(Hα)) *vs.* the 20% width of the HI line in km s^{-1} (σ(HI))in the middle left panel, the blue surface magnitude *vs.* σ(HI) in the middle right panel, the HISFI *vs.* σ(HI) in the lower left panel, and Σ(Hα) *vs.* σ(HI) in the lower right panel. The symbols used are filled diamonds for the BCD galaxies and squares for the LSBs.

Figure 2: Relation between the SFR per unit area [logΣ(Hα)] and logΣ(HI)Ω, a quantity proportional to the gas surface density times a global gas-dynamical measure. The additional symbols with respect to Fig. 1 are filled circles for objects from Martin (1997) and triangles for galaxies from Salzer *et al.* (1995).

Figure 3: Relation between the average SFR per unit area logΣ(Hα) and the average blue surface magnitude. The symbols are as in Fig. 2.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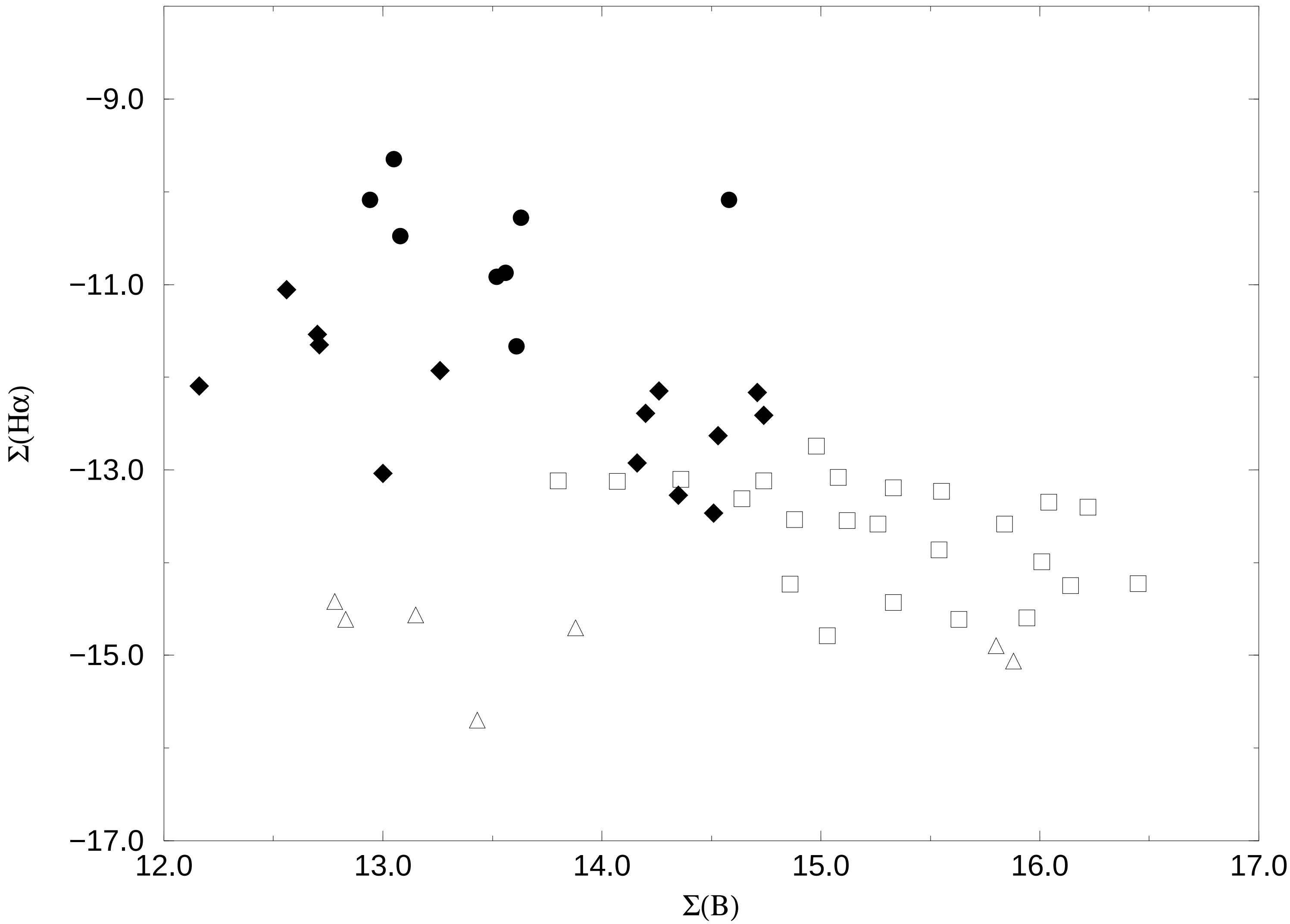
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