Chemical Evolution and Starbursts

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Abstract. The first part of this paper deals with the impact of nonsolar and – for late-type, dwarf, and high redshift galaxies – generally subsolar abundances on the interpretation of observational data for starburst galaxies. It points out the differences in colors, luminosities, emission lines, etc. obtained from a model using low metallicity input physics for a starburst on top of the stellar population of a galaxy as compared to an otherwise identical model using solar metallicity input physics only.

The second part deals with the chemical evolution during a starburst and contrasts model predictions with observational clues.

1 Abundance Effects on Starbursts

The chemical abundances in the gas of a galaxy at the onset of a starburst set the initial abundances for the bulk of the burst stars. Only in long bursts, e.g. like those triggered by interactions between massive galaxies, may later generations of burst stars incorporate SN II products from earlier ones.

Starbursts in giant galaxies, e.g. triggered by an interaction or merger event, are the more spectacular the more gas is available. In the local Universe, a broad anticorrelation is observed between the size and the metallicity of a galaxy’s gas reservoir. Hence, the strongest bursts can be excited in gas rich galaxies which genuinely are of low metallicity. Dwarf galaxies as well as young galaxies generally have lower abundances than today’s giant galaxies.

We will show that for a burst of given strength, the spectrophotometric as well as the chemical evolution are significantly dependent on the metallicity. Interpretation of starburst galaxy observations therefore requires comparison with models of appropriate metallicity.

1.1 Abundances in Local and High Redshift Galaxies

While already in the Milky Way, the global average stellar and gas abundances both are subsolar (\(\sim \frac{1}{2}\) solar), late type galaxies with their huge gas reservoirs show significantly lower abundances still [25,13,34,2,35].

So, strong starbursts in local giant gas-rich galaxies, e.g. triggered by interactions or mergers like in NGC 4038/39 or NGC 7252, are to be described by models accounting for the moderately subsolar metallicity of the gas in these objects. Burst durations in giant galaxies are typically of the order of the dynamical timescale \(\tau_B \sim t_{\text{dyn}} \sim 10^8\) yr, i.e. long compared to the most massive
stars’ lifetimes. Hence self-enrichment in SN II products like O, Mg, and other α-elements during bursts may be important for giant galaxies. Depending on the cooling timescale, these SN II products may even be incorporated into burst stars that form after the first generation of massive burst stars has already died.

**Dwarf galaxies** in the local Universe, according to the luminosity – metallicity relations established both for the stellar metallicities of dwarf elliptical and spheroidal galaxies and for the gas metallicities of dwarf irregular galaxies, show significantly subsolar abundances that extend down to few percent solar \(Z_{\odot}\). E.g., Blue Compact Dwarf Galaxies (BCDs) typically feature \((Z) \sim \frac{1}{10} Z_{\odot}\), extreme examples like IZw18 or SBS 0335-052 reach down to \(\sim \frac{1}{10} Z_{\odot}\). Hence undoubtedly, the interpretation of starbursts occuring in dwarf galaxies requires models of appropriately low metallicity. In recent years, Tidal Dwarf Galaxies (TDGs) have been detected in rapidly increasing numbers, forming in the tidal tails of massive interacting spirals. Compared to dwarf galaxies of comparable luminosity they show enhanced metallicities, typically in the range \((\frac{1}{4} - \frac{1}{2}) Z_{\odot}\), as a result of being formed from stars and pre-enriched gas pulled out from their parent galaxies \([1]\). As for giant galaxies, typical burst durations in dwarf galaxies are of the order of the dynamical timescale, and, hence \(\tau_B \sim 10^6 \) yr for dwarf galaxies. These short burst durations – not longer than the lifetimes of massive stars – imply that self-enrichment during a burst will not be important. Mass loss due to SN-driven galactic winds, on the other hand, may be important for dwarf galaxies due to their shallower potential wells as compared to giant galaxies and may significantly affect their chemical evolution. The occurrence and strength of galactic winds in dwarf galaxies, however, depend on the poorly constrained mass of their dark matter halos.

Galaxies in the early Universe, of course, have lower metallicity than their local counterparts. Lyman Break Galaxies at \(3 < z < 4\), some or many of which are observed in phases of enhanced star formation (SF), show metallicities in the range \((0.1 - 1) Z_{\odot}\) as derived from the restframe UV stellar wind lines of their stellar populations \([18,32]\) and from their [O III] emission lines \([30]\). The ample supply of neutral gas in Damped Lyα Absorbers at \(0 \leq z \leq 4.4\) shows abundances from \(10^{-3} Z_{\odot}\) to \(< \sim Z_{\odot}\) \([21,22]\).

### 1.2 Chemical and Spectrophotometric Evolution Models

In the following we use evolutionary synthesis models to describe the spectrophotometric and chemical evolution of starbursts in various types of galaxies. The models for undisturbed galaxies of various types are parametrised by the respective appropriate star formation histories \(\Psi(t)\) and constrained by the requirement to provide agreement after \(\sim 12\) Gyr of evolution with average colors, luminosities (U ... K), emission and absorption line strengths, characteristic H II region abundances (= measured at \(R_{\text{eff}}\)), and gas content of local samples of the respective types and with template spectra. Then a burst of given strength \(b := \frac{\Delta S}{S}\) (with \(S\) : stellar mass at the onset of the burst, \(\Delta S\) : stellar mass added in the burst) and duration \(\tau_B\) is assumed to start at some time \(t_B\). Using sets
of input physics (stellar evolutionary tracks, lifetimes, stellar yields, model atmosphere spectra, and absorption index calibrations) for a range of metallicities from $10^{-4}$ to 0.05, models follow the spectral evolution from UV – NIR, the chemical evolution of individual gas phase element abundances, as well as the metallicity distribution in the stellar population before, during, and after the burst. Models account for the finite lifetimes of the stars before they give back enriched material, include the contributions of type Ia SNe as described by [19], but they are otherwise kept as simple as possible in order to minimize the number of parameters. In particular, they are closed box 1-zone models and assume instantaneous and perfect mixing of the recycled gas.

1.3 Abundance Effects on Starbursts

At subsolar metallicities, bursts of a given strength in the same type of galaxy lead to higher peak luminosities, bluer optical colors, slower and weaker fading and reddening after the burst (Fig. 1), and higher mass loss from the burst population (due to shorter stellar lifetimes) as compared to models using solar metallicity input physics [14, 16, 26]. Furthermore, at lower metallicities, spectra look different, emission line ratios change [11], the emission contribution of the gas is higher to UBVR fluxes and lower in JHK bands (Fig. 2), UV stellar wind lines are weaker [17], and dust extinction less important.

Hence, in a low metallicity galaxy, the same blue optical colors imply a weaker or older burst than they would in a solar metallicity galaxy.

2 Chemical Evolution in a Starburst

2.1 Model Predictions

The chemical evolution – both in terms of ISM enrichment and metallicities of stars formed in the burst – depends on the burst strength, the size of the gas

![Fig. 1. Color-color diagram for starburst models at two different metallicities and 3 burst strengths each (b=0.1, 0.01, 0.001) on top of a galaxy with const. SF rate. ☓ marks the galaxy before the burst, * the color of the pure gas spectrum. BCD data are from [31].](image)
reservoir, and on the (time of) occurrence or non-occurrence of SN-driven galactic winds or superwinds. The latter, unfortunately, depends on several poorly known conditions, e.g. on the masses of DM halos, the geometry of the starburst region, etc. Note that the same number of burst stars can cause vastly different increases of the ISM metallicity depending on whether they shed their enrichment products into a small or a large gas reservoir. During a burst, individual element abundances in the ISM increase on individual timescales, depending on the nucleosynthetic origin of the respective element. Oxygen and other typical SN II products (α-elements) are restored on very short timescales given by the lifetimes of massive stars. Thus the abundances of oxygen and other α-elements start increasing shortly after the onset of the burst and do not continue for long after its end. Elements that are predominantly synthesized in intermediate mass stars, like C or N, as well as elements that have important contributions from type Ia SNe, such as Fe, only start enriching with certain time delays after the beginning of the burst and continue to do so for up to some Gyr after the end of the burst. This effect leads to strong changes in the element ratios between elements of different nucleosynthetic origin. As e.g. [24] showed, the large range of N/O-ratios at essentially all oxygen abundances among dwarf galaxies, Galactic and extragalactic HII regions may be explained by successive bursts of SF. During a short burst, the oxygen abundance increases and, hence N/O decreases while nitrogen is not changed yet. The nitrogen abundance only starts increasing after the end of the burst, leading to an increase of N/O at essentially constant oxygen abundance during up to a few Gyr.

A detailed understanding of the chemical evolution in the course of a starburst not only requires a consistent chemodynamical model but also the consideration of the multi-phase nature of the ISM, including a full description of all kinds of transition processes between the hot X-ray gas, the warm and neutral (HI) components and the cold and clumpy molecular gas. This latter compo-
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ponent, often traced by CO, is increasingly difficult to observe in low metallicity dwarf galaxies. A consistent and complete model including all these phases and processes is still to be developed [24].

2.2 Observational Clues

ISM Abundances H II region abundances in BCDs are used to obtain the metallicity of the stars formed in the burst. Burst strengths in BCDs are weak as compared to those in massive gas rich interacting galaxies, increasing the stellar mass by typically few percent or less [15]. H I reservoirs, on the other hand, are large in BCDs. So, the metallicity increase in the burst and, hence, the metallicity difference between preburst and burst stars both are relatively small.

This explains why models using input physics for the H II region metallicity observed in a BCD generally also allow for good agreement with its spectral energy distribution which, at short wavelengths, is dominated by burst stars while at long wavelengths (JHK) it is mostly due to the preburst component [15].

TDGs, on the other hand, with their observed H II region abundances enhanced over those of dwarf galaxies of comparable luminosity, in most cases turn out to be well describable with models including an old stellar population from a late type galaxy plus a burst star component of $<\frac{1}{2}$ solar metallicity [33]. Their H II region abundances indeed are $[O/H]_{TDG} > [O/H]_{ISM}$ spiral.

Stellar and Star Cluster Abundances Stellar abundances for starburst populations are difficult to disentangle observationally from those of the preburst stars. Star clusters formed in starbursts in some dwarf galaxies and – in huge numbers – in the strong bursts accompanying gas rich galaxy mergers, however, provide a powerful tool to study the chemical enrichment process in these bursts. As opposed to field stars, they well separate from the preburst population and can be analysed individually.

Models predict their abundances on the basis of the progenitor galaxy ISM abundances and gas reservoirs, and of the strength and duration of the burst. E.g. for the young and very young star cluster populations in NGC 7252 and NGC 4038/39 average metallicities of $(\frac{1}{2} - 1)Z$ were predicted as well as some $\alpha$-enhancement for the youngest clusters in the almost 1 Gyr old burst in NGC 7252 [6]. [10] and [26] show how significant the metallicity of a star cluster is in interpreting its photometric data, e.g. for age-dating and mass estimates. Young star clusters are bright – at ages of $\sim 10^8$ yr typically 4 mag brighter than old globular clusters (GCs) of the same mass. 10 m telescope spectroscopy thus directly gives access to metallicities, ages, velocity dispersions for kinematic mass estimates, ... [10][26][25].

For clusters older than few $10^8$ yr which no longer feature emission lines, stellar absorption features in comparison with theoretical model calibrations at the appropriate young ages [6][24] give information about individual element abundances and abundance ratios. With spectroscopy of reasonable samples the
metallicity and age distributions among young star clusters and their spatial variations will give information about the dynamics of the burst and its detailed enrichment process. The limiting factor for this kind of observations is the strong and spatially variable galaxy background.

MOS of old GCs is within reach of 10m telescopes out to Virgo cluster distances. The metallicity distributions this will reveal for the old GC populations of elliptical and S0 galaxies will teach us a lot about their formation processes [36,9].

3 Conclusions

Accounting for the appropriate metallicities in evolutionary synthesis models is essential for the interpretation of starburst galaxies as is the consideration of dust (see S. Charlot, this vol.).

In a burst, we see to first order star formation and ISM abundances at the metallicity of the gas in the preburst galaxy. Most clearly this is seen on star clusters rather than on field stars. Only to second order metallicity and, in particular, α-enhancements are expected in the long lasting bursts in massive interacting gas rich galaxies. Again these are best studied on individual star clusters.

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References

1. P.A. Duc, I.F. Mirabel: IAUSS 186, 61 (1999)
2. A.M.N. Ferguson, J.S. Gallagher, R.F.G. Wyse: AJ 116, 673 (1998)
3. U. Fritze – v. Alvensleben: A&A 336, 83 (1998)
4. U. Fritze – v. Alvensleben: A&A 342, L25 (1999)
5. U. Fritze – v. Alvensleben: in Massive Stellar Clusters, eds. A. Lanon, C. Boily, ASP Conf. Ser. 211 (ASP, San Francisco, 2000) p.3
6. U. Fritze – v. Alvensleben, A. Burkert: A&A 300, 58 (1995)
7. U. Fritze – v. Alvensleben, O.E. Gerhard: A&A 285, 751 (1994)
8. U. Fritze – v. Alvensleben, O.E. Gerhard: A&A 285, 775 (1994)
9. K. Gebhardt, M. Kissler – Patig; AJ 118, 1526 (1999)
10. L.C. Ho, A.V. Filippenko: ApJ 472, 600 (1996)
11. Y.I. Izotov, T.X. Thuan: ApJ 511, 639 (1999)
12. Y.I. Izotov et al. : ApJ 527, 757 (1999)
13. J. Kilian - Montenbruck, T. Gehren, P.E. Nissen: A&A 291, 757 (1994)
14. H. Krüger, U. Fritze - v. Alvensleben: A&A 284, 793 (1994)
15. H. Krüger, U. Fritze - v. Alvensleben, H.-H. Loose: A&A 303, 41 (1995)
16. O. Kurth, U. Fritze - v. Alvensleben, K.J. Fricke: A&A 138, 19 (1999)
17. C. Leitherer et al. :ApJS 123, 3 (1999)
18. J.D. Lowenthal, D.C. Koo, R. Guzman, et al. : ApJ 481, 673 (1997)
19. F. Matteucci, A. Tornambé: A&A 142, 13 (1985)
20. F. Matteucci, M. Tosi: MNRAS 217, 391 (1985)
21. M. Pettini, L.J. Smith, R.W. Hunstead, D.L. King: ApJ 426, 79 (1994)
22. M. Pettini, S.L. Ellison, C.C. Steidel, D.V. Bowen: ApJ 510, 576 (1999)
23. M.G. Richer, M. McCall: ApJ 445, 642 (1995)
24. A. Rieschick, G. Hensler: AGM 17, 72 (2000)
25. H.J. Rocha - Pinto, W.J. Maciel: A&A 339, 791 (1998)
26. Schulz et al., in preparation
27. F. Schweizer, P. Seitzer: ApJ 417, L29 (1993)
28. F. Schweizer, P. Seitzer: AJ 116, 2206 (1998)
29. E.D. Skillman, R.C. Kennicutt, P.W. Hodge: ApJ 347, 875 (1989)
30. H.J. Teplitz et al.: ApJ 542, 18 (2000)
31. T.X. Thuan: ApJ 268, 667 (1983)
32. S.C. Trager, S.M. Faber, A. Dressler, A. Oemler: ApJ 485, 92 (1997)
33. P.M. Weilbacher, P.A. Duc, U. Fritze - v. Alvensleben, P. Martin, K.J. Fricke: A&A 358, 819 (2000)
34. D. Zaritsky, R.C. Kennicutt, J.P. Huchra: ApJ 420, 87 (1994)
35. L. van Zee, J.J. Salzer, M.P. Haynes et al.: AJ 116, 2805 (1998)
36. S.E. Zepf, K.M. Ashman: MNRAS 264, 611 (1993)