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The nature of the massive stellar transient in DDO 68

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Abstract: When measuring the metallicity of several H II regions in the very low metallicity dwarf galaxy DDO 68, Pustilnik et al. (2008) noted a spectral change of one H II region within 2 years. The lines in the residual spectrum and the brightening of the continuum lead them to interprete this transient event to be due to a variable massive star. Using archival and new imaging and spectroscopy of DDO 68, we present a study of the variability of the transient. Using the derived photometric variability and the properties of its spectrum, we noted that the transient appears to the very similar to V1 in NGC 2366, an exceptional LBV-like object. Together with results on massive variable stars in other nearby, low metallicity galaxies, this indicate interesting twists for the evolution of massive stars at metallicities below that of the Magellanic Clouds. Based on our compilation of nearby, very metal-poor galaxies, there are several objects suitable for observational studies of massive stars at very low metallicities with the current ground and space based instrumentation. This opens the window to derive observationally parameters of stars and their feedback on the interstellar medium critical for analyzing the galaxies at high redshift up to the time of reionization.

1 Why is very low metallicity exciting?

It is long known from theory of stellar evolution and stellar atmospheres that there are significant changes when going to stars at low metallicity. These effects are already apparent in the Magellanic Clouds, which provide nice laboratories for massive stars at 0.4 and 0.2 of solar metallicity. Still, there is a significant gap between the metallicities of the Magellanic Clouds and the metallicities observed at high redshifts, despite a significant spread of metallicities observed in DLA and Lyman break galaxies. This is especially true for the epoch of galaxy formation to the end of reionization ($z > 6$) (Schaerer & de Barros 2010). Observational studies of massive stars at metallicities significantly below 1/10 of solar are therefore important for our understanding not only of galaxy formation but also stellar feedback at high redshift. Massive stars and subsequent supernovae provide the energy input driving galactic outflows and winds (Leitherer, Robert, & Drissen 1992), which are critical ingredients of galaxy formation and evolution. At very low metallicity, stellar evolution, stellar atmospheres, and the instabilities in stars should be very different. This effects stellar winds, late evolutionary phases, variability, (evolution of) rotation, convection, SN types, binary star evolution, and progenitors of long GRBs.

2 Nearby very low metallicity galaxies

To get a better handle on the stellar population and their time dependent energy input to their host galaxies in the early universe, observations of the best possible local proxies are mandatory. Unfortunately, such extreme metal-poor galaxies (metallicities of less than ~1/10 of solar) are quite rare objects (e.g., Kunth & Östlin 1999). The prototype for such galaxies is I Zw 18. Not surprisingly, it was repeatably observed with HST, but it turned out to be quite difficult to study due to high crowding, high and variable background and faintness of its stars. I Zw 18 has now a securely determined distance of 18 Mpc (Aloisi et al. 2007; Fiorentini et al. 2010), which places it beyond the reach for ground-based studies of its stars. The analysis of the HST data material showed that I Zw 18 does contain five periodic variables, 3 of them inside the Cepheid instability strip (2 of the Cepheids have periods $>$ 100 days), and 34 candidate/non-periodic variables (Fiorentino et al. 2010). Since the Meynet & Maeder (2005) rotation models imply an extension of the mass range of stars with LBV-like instabilities downward (e.g., Weis 2011), the location of the brightest and bluest of these candidate variables in I Zw 18 is consistent with the CMD location of rapidly rotating LBV-like stars. Additionally, 5 to 9 Wolf-Rayet stars appear to be present in I Zw 18 (de Mello et al. 1998).

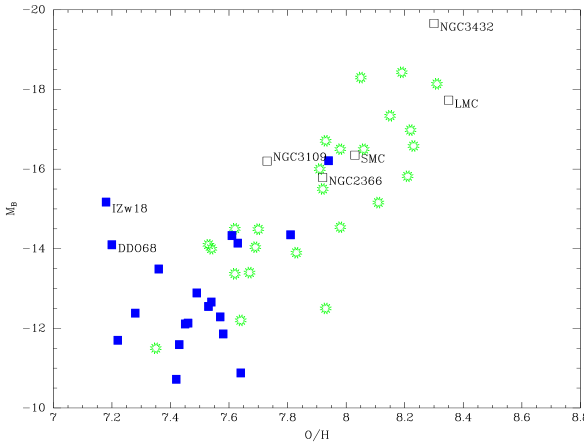

Figure 1: Metallicity-luminosity relation of the sample of local dwarf galaxies compiled by Lee et al. (2006) (green open sun symbols), several comparison galaxies (black open squares) and the nearby low metallicity star forming galaxies compiled by us (blue filled squares). It is potentially important to note that I Zw 18 and DDO 68 are both very luminous for their metallicity, which may imply that we catch them right in a significant burst of star formation, which leads to a temporary elevation of their B-band luminosity.

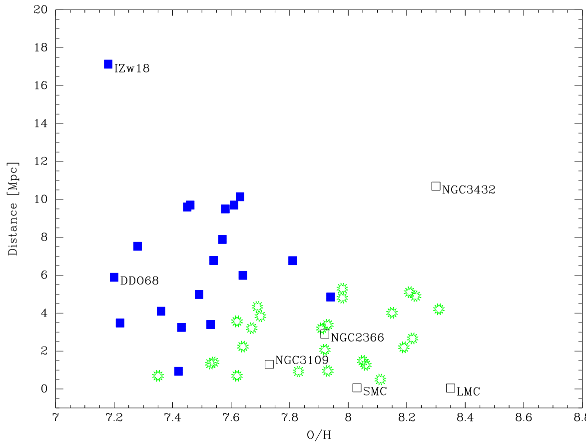

Figure 2: Metallicity-distance diagram of the same galaxy samples as plotted in Fig.1 and with the same symbols. It is clear that with its new, large distance, I Zw 18 is not the most ideal laboratory to perform observational studies of very low metallicity massive stars. Depending on the targets (e.g. extremely massive stars, Cepheids, red hyper- and supergiants, ...) there are several much closer objects. With its current high star formation rate, DDO 68 is definitely a prime target for the study of extremely massive stars at low metallicity.

Clearly, for detailed studies of massive stars at these metallicities, more targets at lower distances are important. The basic problem to reach this aim is that such low metallicities are found locally only in low mass galaxies (e.g., Lee et al. 2006). Therefore a significant recent star formation rate in these galaxies is needed to ensure useful sample sizes of (very) massive and therefore short lived stars. The short evolutionary time scales therefore imply that not every low metallicity dwarf galaxy will provide examples of all short lived, transitional phases. The recent star formation history enters as a critical parameter.

3 Very low metallicity galaxies in the local volume

Which are the galaxies with significant recent star formation at low metallicity and how many do exist in the Local Volume? As Local Volume we define here the sphere with 11 Mpc radius of the Milky Way. It is roughly the maximal volume in which massive single stars are accessible for detailed spectral analysis with 10 m class ground-based telescopes, e.g., Bresolin et al. (2001). A 10 or 11 Mpc definition of the "Local Volume" is also used for several survey projects recently, e.g. 11HUGS (Kennicutt et al. 2008) or LVHIS (Koribalski 2008). The problem for the study of single stars out to these distances is not only the faintness of the targets but also the spatial resolution. Dense groups and clusters of massive stars become unresolved, or just barely resolved, producing a significant light contamination to targets in or near them. In the case of luminous transients, like LBV outbursts, these problems are significantly reduced, as the star outshines its environment. In such a case the Local Volume may be even a conservative limit, see for example the LBV transient in NGC 3432 at a distance of 10.7 Mpc (Pastorello et al. 2010). In the case of very bright transients, time enters the problem. Due to their transient nature, they will unpredictively be bright enough for study. The other problem is that studying only these transient introduces a classical Malmquist bias to a lot of the analyses. We started to compile a data base of very low metallicity local galaxies, the current state of it is plotted in Fig.1 and 2. While I Zw 18 is clearly not the best target anymore, it is doable with the HST, and several more potentially useful targets within 8 Mpc are apparent.

4 Luminous transients at low metallicity

DDO 68 is an extremely low metallicity galaxy with an abundance of ∼1/40 solar. When taking a spectrum of a H II knot in 2008, Pustilnik et al. (2008) noted that it is significantly different from a spectrum taken 3 years earlier. The difference spectrum clearly showed P Cygni profiles in the Balmer lines and a blue continuum. The authors suggested that their finding is the brightening of an LBV, an interpretation later supported by Izotov & Thuan (2009).

Still, one should still be skeptical, since slight misalignment between the slit position of the observations in such a relatively distant (D $\sim$ 8 Mpc) and a complex background may lead to spurious results. To check the presence of a variable source, we compiled a ground-based light curve of the object using own and archival imaging data. The result is plotted in Fig.3. Clearly, the knot is variable by more than 1 mag over the last 50 years. If the measurement from 1988 defines the quiescent state of the most luminous star in the knot, than the star showed brightening by > 2 mag since then. For the interpretation one has to keep in mind that these measurements are integrated values for the unresolved (or barely resolved) ionizing cluster of an H II region. The age of the cluster should be below 3×10^6 yr to provide enough Lyman continuum photons. Our preliminary STARBURST99 (Leitherer et al. 1999) simulations even imply $\sim 1 \times 10^6$ yr (Bomans & Weis 2011).

All these pieces of evidence seem to be consistent with a very massive, highly variable star, dominating the luminosity and color of the cluster in its bright phases. Before jumping to the interpretation of an LBV, there are a few odd aspects: the brightening appears to be at constant or bluer color, which excludes a classical S Dor variability (e.g., van Genderen 2001). The wind terminal velocity estimated from the 2008 difference spectrum is $\sim$800 km s^{-1}, which looks more more like a wind than mass ejection event (a giant eruption).

In this context, it is interesting to look at NGC 2366, a strongly star forming (Lee et al. 2009) dwarf irregular galaxy at a distance of $\sim$ 3 Mpc and a metallicity of $\sim$ 1/10 solar. The massive stars are clearly driving material out into the halo of this galaxy (Martin 1998; van Eymeren et al. 2009), making it a good laboratory for stellar feedback studies. In NGC 2366, Drissen et al. (2001) noted the sudden appearance of a stellar source inside its brightest giant HII region. They found an increase

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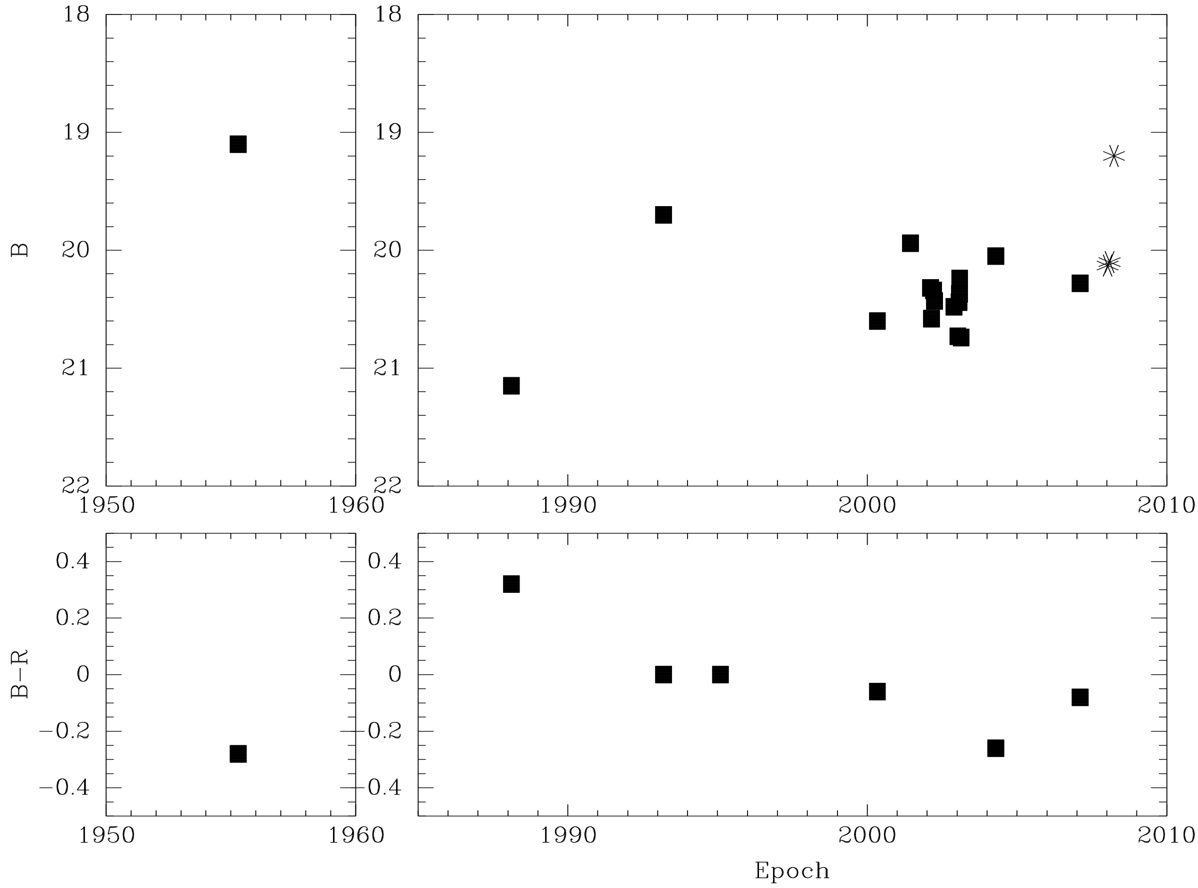

Figure 3: Lightcurve of the cluster plus transient source in DDO 68. Black squares are archival and our photometric data (mostly from CCD), asterisks denote spectroscopic fluxes converted to B band magnitudes. Clearly, there is a very luminous, variable star in the cluster.

by 3.1 mag to V ~ -10.2 mag and a rise in brightness while getting hotter (bluer colors). The spectra changed with time (Petit et al. 2006) and the early spectra are similar to the one of the DDO 68 transient. Again the spectra are more like wind instead of sudden mass ejection (giant eruption) with a wind terminal velocity $\sim 250\,\mathrm{km\,s^{-1}}$.

There appear to be similarities between the DDO 68 transient and NGC 2366 V1. One is tempted to speculate that we see a LBV-like variability, but somewhat different from classical S Dor cycle. Within that cycle the star should encounter the bistability jump, which is function of metallicity. This might lead to a less pronounced change in the star's spectrum (and the S Dor variability) and may yield a different spectroscopic behavior for LBVs like DDO 68 transient and NGC 2366 V1 (see e.g., Weis 2011).

5 Conclusions

So, what can be learned from the data collected up to now?

On the observational side, even if I Zw 18 is more of an HST (and in the future a (challenging) adaptive optics) target, there are several galaxies in the Local Volume with metallicities close to or only slightly higher than the one of I Zw 18, which enable us to observationally study the properties and evolution of massive very low metallicity stars.

Of these galaxies, DDO 68 is of special interest, not only because its metallicity is indeed very low, but also because it appears to contain a very luminous transient star. The information collected up to now appear to imply that it is similar in may aspects to V1 in NGC 2366, which was interpreted a a strange LBV-like star. NGC 2366 is a nearby, quite metal-poor starbursting dwarf galaxy itself (see e.g. Fig.2). The similarity between the transient source in DDO 68 and V1 in NGC 2366 may imply that the instabilities leading to LBV-like variability and/or eruptions work somewhat differently at low metallicity, or that different processes/instabilities are at work at these low metallicities.

The observational results on the transient in DDO 68, together with HST results on I Zw 18 (e.g. Fiorentino et al. 2010), and first results on massive variable stars in other low metallicity dwarfs (e.g. Hoessel, Saha, & Danielson 1998; Herrero et al. 2010; Bomans & Weis 2011) point at interesting differences of properties and evolution of these stars compared to stars in the Large and Small Magellanic Clouds, our “normal” template galaxies for low metallicity stars.

One can conclude, that there is a direct observational access to many parameters of interest for the stars and their feedback onto the interstellar medium and high redshift, maybe up into the age of the reionization.

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