TYPE Ib/c SUPERNOVAE IN DISTURBED GALAXIES: EVIDENCE FOR A TOP-HEAVY INITIAL MASS FUNCTION

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ABSTRACT

We compare the radial locations of 178 core-collapse supernovae (CCSNe) to the R-band and Hα light distributions of their host galaxies. When the galaxies are split into “disturbed” and “undisturbed” categories, a striking difference emerges. The disturbed galaxies have a central excess of CCSNe and this excess is almost completely dominated by supernovae of types Ib, Ic, and Ib/c, whereas type II supernovae dominate in all other environments. The difference cannot easily be explained by metallicity or extinction effects, and thus we propose that this is direct evidence for a stellar initial mass function that is strongly weighted toward high-mass stars, specifically in the central regions of disturbed galaxies.

Key words: galaxies: interactions – galaxies: ISM – supernovae: general

Online-only material: machine-readable tables

1. INTRODUCTION

Following the pioneering work of Larson & Tinsley (1978), many studies have confirmed that tidal disturbance following galaxy interactions is an efficient trigger of star formation in galaxies (e.g., Joseph et al. 1984; Kennicutt & Keel 1984). Such star formation frequently takes the form of centrally concentrated nuclear starbursts (Joseph & Wright 1985), fuelled by the central concentrations of molecular gas found to occur naturally in simulations of highly disturbed systems (Barnes & Hernquist 1991; Mihos & Hernquist 1996). The strength of the link between starbursts and interactions was highlighted by the finding that almost all of the “ultra-luminous infrared galaxies” display signs of interactions or mergers (Sanders et al. 1980; Borne et al. 1999) and by correlations between galaxy–galaxy separations and starburst strength (Barton et al. 2000). Even minor mergers with low-mass companions have been shown through simulations to result in significant nuclear star formation activity (Mihos & Hernquist 1994).

Several early studies of nuclear starbursts suggested that this star formation might require a top-heavy initial mass function (IMF), preferentially producing high-mass stars (Rieke et al. 1980; Doyon et al. 1992). There is theoretical support for this suggestion, with simulations showing that an IMF weighted to high-mass stars naturally arises in high-density regions due to feedback processes heating the gas. In a recent study, Krumholz et al. (2010) have demonstrated that such regions should have a high-mass stellar fraction at least 1.7 times larger, and possibly much more, than lower density, more quiescent regions.

However, the observational evidence for this variation has to date proved controversial (see Bastian et al. 2010 for a recent review). Some studies have found indirect evidence for top-heavy IMFs with, for example, Rieke et al. (1993) concluding that the nearby starburst galaxy M82 requires an IMF biased to high-mass stars to explain its emission line ratios and total luminosity. Similar techniques have been used for NGC 3256 (an ongoing merger with a “super-starburst”) and which have again shown indications of a modified IMF with an excess of high-mass stars (Doyon et al. 1994). Gibson & Matteucci (1997) showed that, in order to reproduce the observed color–luminosity relation of elliptical galaxies, an IMF much flatter than that of Salpeter (1955) needed to be adopted. Baugh et al. (2005) had to employ a top-heavy IMF for the starbursts powering the distant population of highly luminous submillimeter galaxies in order to explain the number counts of these systems. Finally, Brassington et al. (2007) studied nine interacting galaxies from the Chandra survey and found that highly disturbed systems showed a strongly enhanced infrared luminosity compared to that expected from the X-ray emission, again suggesting the need for a top-heavy IMF.

More direct evidence of a variation in IMF has been found for the resolved stellar population of the young Arches cluster in the Galactic center. Figer et al. (1999), Stolte et al. (2002), Paumard et al. (2006), Espinoza et al. (2009), and Bartko et al. (2010) all find evidence for stellar mass functions weighted toward high-mass stars in this cluster or the general Galactic center region. Such mass functions are parameterized as an IMF that is either much flatter than that found by Salpeter (1955) or having a higher mass turnover than is found in the function for field stars.

One possible tracer of the IMF that has not been fully exploited to date is the relative numbers of core-collapse supernovae (CCSNe) of different types. Their short progenitor lifetimes and high luminosities make them powerful indicators of recent or ongoing star formation, and indeed they provide the only direct tracer of recent star formation within unresolved stellar populations. Recent advances in the understanding of supernovae and their progenitors raise the possibility that they can provide information on the initial mass function of a young stellar population. Theoretical models of single star progenitors predict that type II supernovae (SNII) should have lower mass progenitors than type Ib supernovae (SNIb) or type Ic supernovae (SNIc) (Heger et al. 2003; Eldridge & Tout 2004). This has received observational support from studies of the strength of association with Hα emission (Anderson & James 2008), confirming that SNII have the lowest mass CC progenitors, but additionally indicating that the SNIc have still higher mass progenitors than the SNIb. The existence of this II–Ib–Ic progenitor mass sequence allows information on the IMF of the stellar population in SN environments.
to be derived from the relative numbers of type II, Ib, and Ic supernovae.

Petrosian & Turatto (1995) studied the distribution of SNe events in 32 interacting systems containing 12 known CCSNe. They found that the radial distribution of these core-collapse events showed a higher concentration toward the nuclear regions of the interacting galaxies when compared to isolated galaxies. This confirmed the enhanced star formation around the central regions of the systems, but the sample was too small to analyze the separate types of CCSNe.

This paper will therefore use a larger sample of local CCSNe to explore the IMF in nuclear starbursts, resulting from galaxy disturbance, by studying the ratio of type II/Ibc SNe in both disturbed and undisturbed host galaxies. Throughout this paper, we use “Ibc” to encompass all SNe with classifications of Ib, Ic, or Ib/c.

The paper is organized as follows. In Section 2, we will define and discuss the sample used throughout this work. Section 3 will describe the results on the radial distributions, for disturbed and undisturbed hosts, and look separately at type II and Ibc SNe. In Section 4, we discuss the possible interpretations of our results in terms of metallicity, extinction, and IMF effects. Finally, Section 5 contains a summary of our conclusions.

### 2. SAMPLE AND OBSERVATIONS

The sample used in this work consists of 140 local (recession velocity <6000 km s⁻¹) spiral galaxies, hosts to 178 CCSNe (110 SNII and 68 SNIbc), for which we have Hα and R-band observations from the Liverpool Telescope and Isaac Newton Telescope. (Some galaxies do not have usable images in either Hα or R-band and have been omitted from the corresponding plots and statistics; see Tables 1 and 2 in the online journal). This is the same data set as used by Anderson & James (2009) with a small number of subsequent observations. SNe classified as type IIb are not included in this sample as they are thought to be transitional objects between SNII and SNIb, with substantially larger progenitor masses (≈25 M☉; Smartt 2009) than typical SNII. A comparison performed on 2010 January 21 with all CCSNe host galaxies within the same recession velocity limit in the IAU SN catalog, where the SNe have accurate classifications and positions, showed this sample to be ≈34% complete for SNIbc and ≈18% complete for SNII.

The classification of host galaxies as disturbed is purely by visual inspection by the authors and thus is subjective. Galaxies which show signs of tidal tails, definite interaction, double nuclei or strong asymmetry have therefore been classed as disturbed.

### 3. RESULTS

The total sample of CCSNe is dominated by SNII (62% of the total). When the sample is constrained only to supernovae which lie in disturbed hosts (64 CCSNe), this falls to 56% SNII compared to 65% SNII in the non-disturbed hosts.

For each of the CCSNe in our sample, we have calculated the Fr(R) and Fr(Hα) statistics used, and explained fully, in Anderson & James (2009). Briefly, these represent the fractions of galaxy emission in the R-band and Hα, respectively, that lie within the circle or ellipse which contains the SN. Thus, Fr(R) = 0.0 corresponds to a supernova at the central 50% of the galaxy emission, or closer to this peak than any Hα emission, in the case of Fr(Hα), while Fr = 0.5 implies an extreme outlying SN. If the emission is statistically a good tracer of the parent population of supernovae, the Fr values should have a flat distribution with a mean value of 0.5.

Figures 1 and 2 show the distributions of Fr(R) values for the CCSNe in the present sample for the undisturbed and disturbed galaxies, respectively. In all histograms shown in this paper, the upper plot represents the CCSNe sample, the middle the type II SNe, and the lower, SNIbc. Looking first at the overall distributions of CCSNe, there is a clear difference between the disturbed and undisturbed subsets, in the sense that the disturbed galaxies have substantially more CCSNe occurring in their central regions, with low Fr(R) values. For example, 36 of the 58 CCSNe in the disturbed sample occur within the central 50% of the R-band light, 62% of the total, compared with 50 out of 112 (45%) in the undisturbed galaxies. A Kolmogorov–Smirnov (K-S) test shows that the chance of the two total CCSNe distributions being drawn from the same parent distribution is P = 0.037. Thus, there is evidence at the 2σ level that galaxy disturbance correlates with centrally enhanced star formation and hence the production of an increased central fraction of CCSNe.

The most striking aspect of Figure 2 is the types of SNe that make up this central excess in the disturbed galaxies.

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**Table 1**

| Host    | SN   | SN Type | Fr(R) | Fr(Hα) |
|---------|------|---------|-------|--------|
| NGC493  | 1971S| II      | 0.605 | 0.570  |
| NGC918  | 2009js| II     | 0.703 | ...    |
| NGC941  | 2005ad| II     | 0.831 | 0.664  |
| NGC991  | 1984L | Ib     | 0.498 | 0.401  |
| NGC1035 | 1990E | II     | 0.272 | 0.363  |
| NGC1058 | 1961V | II     | 0.968 | 0.931  |
| NGC1058 | 1969L | II     | 1.000 | 1.000  |

**Table 2**

| Host    | SN   | SN Type | Fr(R) | Fr(Hα) |
|---------|------|---------|-------|--------|
| NGC895  | 2003ld| Ic      | 0.524 | ...    |
| UGC2984 | 2002jz| Ic      | 0.091 | 0.099  |
| NGC1614 | 1996O | Ic      | 0.275 | 0.275  |
| NGC1637 | 1999em| II      | 0.276 | 0.268  |
| IC391   | 2001B | Ib      | 0.062 | 0.060  |
| NGC1961 | 2011s | Ib      | 0.033 | 0.249  |
| NGC2207 | 1999ec| Ib      | 0.033 | 0.091  |
| NGC2207 | 2003H | Ib      | 0.033 | 0.005  |

**Note.** Columns 1–5 represent the host galaxy, the individual SNe, the spectral classification of the SNe, the fractional R-band light, and fractional Hα values for each SNe, respectively.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Remarkably, given that SNIbc only comprise 38% of the overall CCSN sample (68/178), all 5 of the CCSNe coming from the central 10% of the disturbed host galaxy light and 11 of the 13 coming from the central 20% of the light are of type Ibc. A K-S test of the Fr(R) distributions for the disturbed galaxy subsample finds $P = 0.003$, indicating a very low probability that the SNIbc and SNII Fr(R) values are drawn from the same parent distribution. The mean values of Fr(R) are 0.31 (95% confidence limits 0.20–0.42) for the SNIbc in the disturbed galaxies, compared with 0.51 (0.44–0.59) for the SNII in the disturbed galaxies. This is the main observational result from this paper; the CCSNe occurring in the central regions of disturbed galaxies are heavily weighted toward types Ib, Ic, and Ib/c. We will discuss possible interpretations of this in Section 4.

Some further statistical tests were also performed on the CCSN distributions shown in Figures 1 and 2. Figure 1 shows that even in the undisturbed galaxies, there is some evidence for a larger fraction of SNIbc in the central regions, principally due to a central “hole” in the radial distribution of SNII. A K-S test applied to the SNIbc and SNII distributions shown in Figure 1 shows this difference to be only marginal, $P = 0.082$, and hence clearly less marked than for the disturbed galaxies; disturbance does seem to play a part in the central concentration of the SNIbc. This point was further explored by comparing the SNIbc distributions for undisturbed and disturbed galaxies, i.e., Figure 1 versus Figure 2; this did indicate the SNIbc in disturbed galaxies to be more centrally concentrated, with a K-S $P$ value of 0.06, again of marginal significance. The mean SNIbc Fr(R) value is 0.48 (0.38–0.57) for the SNIbc in the undisturbed galaxies, again to be compared with 0.31 (0.20–0.42) already quoted for the disturbed galaxies. Finally for Figure 2, it might be asked whether there is evidence for a suppression of SNIbc fraction in the outer regions of these galaxies. However, given the current sample size, this cannot be determined with any significance. For example, we find six SNIbc in the outer 50% of the light distributions of the disturbed galaxies, but with only 22 CCSNe in total from these regions, this is not significantly below the expectation value of 8.4, based on the SNIbc/SNII ratio for the full sample.

Figures 3 and 4 show the distributions of supernova locations relative to the H$\alpha$ distributions of their host galaxies. Overall these show the same patterns as Figures 1 and 2, but they do enable one specific issue to be addressed: are the SNIbc more centrally concentrated than the H$\alpha$ light, which is presumably a good tracer of the youngest stellar population? Figure 4 shows that there is some evidence for this; the central 10% of the
He emission in the disturbed galaxies gives rise to 7 of the 22 SNIIbc in these galaxies. The mean Fr(He) value for the SNIIbc in disturbed galaxies is 0.33 (0.21–0.45), so this population does seem to be more centrally concentrated than the He emission. This is not true for the SNIIbc in the undisturbed galaxies or for the SNII in either of the galaxy subsets: all of these distributions have mean Fr(He) values consistent with 0.5.

4. DISCUSSION

Anderson & James (2009) found a central excess of SNIIbc in an SN-host galaxy sample. This work has found that this central excess is exaggerated in galaxies which appear disturbed. A more centrally located distribution of SNIIbc has been suggested previously (e.g., Bartunov et al. 1992; Petrov & Turatto 1995; van den Bergh 1997), though previous studies often suffered from low number statistics. Hakobyan et al. (2009) also find SNIIbc to be more centrally located than SNII; however, in conflict to our results they do not find the central excess of SNIIbc clearly seen in our data. An important difference between our work and most other studies in the literature is that our method implicitly normalizes the tests to the measured distributions of different stellar populations; other studies use distances normalized to isophotal radii. Most of these results have been interpreted as an increase in metallicity of the SNIIbc progenitors, although Hakobyan et al. (2009) also make the suggestion of a shallower IMF within the central regions.

Studies conducted into active and star-forming galaxies (Petrov & Koleva 1997) and Seyfert galaxies (Bressan et al. 2002) have also noted marginal evidence for an increased fraction of both CCSNe and specifically SNIIbc within these galaxies when compared to “normal” ones.

There are various observational biases that may affect our analysis. Shaw (1979) found a bias in supernova samples, in the sense that it is more difficult to detect SNe in the inner regions of distant galaxies. The sample is also subject to any bias contained within the object selection found in the Asiago (Barbon et al. 2009) and IAU SN catalogs. For the Asiago and Crimean searches, Cappellaro et al. (1993) estimated the number of SNe lost due to overexposure combined with the Shaw effect, which for the velocity range of our sample is ∼35%. Another source of bias is the loss of SNe in the central regions of galaxies through the large amount of dust obscuration, which has been investigated through near infrared studies (e.g., Mattila et al. 2007; Kankare et al. 2008). Such biases should affect all SN types, although the intrinsically fainter SNIIP (Richardson et al. 2002, 2006) may be rather more likely to be lost through these effects. However, if our results are correct and SNIIbc are more centrally concentrated than SNII, then recovering all of the lost central SNe would lead to an even more exaggerated excess.

One possible source of error is our eyeball classifications of host galaxy disturbance. In the future, we plan to quantify this through near-IR observations and the use of objective measures of asymmetry (Conselice et al. 2000; Lotz et al. 2004). However, we are quite confident in our disturbance classifications; images of 12 of our “disturbed” galaxies with centrally located SNe are shown in Figure 5, confirming that this is not a “normal” group of galaxies.

The high central excess of SNIIbc in the central regions of the disturbed host galaxies found in this work is difficult to explain in terms of effects other than an IMF biased toward high-mass stars. A possible alternative explanation is the effect of metallicity, given that Boissier & Prantzos (2009) find that the ratio of SNIIbc/SNII increases with both local and global metallicity. Looking at the absolute magnitudes of the host galaxies, we do indeed find that the disturbed galaxies are somewhat more luminous than the undisturbed galaxies (K-S probability of 0.07 that they are drawn from the same parent distribution) by almost 0.4 mag in the mean, which might imply a somewhat higher mean metallicity in the disturbed galaxies. However, this does not seem to be driving the result we find. Splitting the total sample (disturbed and undisturbed) by absolute magnitude, we find no significant differences in the Fr(R) distributions of bright and faint galaxies. Splitting into bright and faint halves, the K-S probability is 0.998 (complete consistency), whereas when the bright third is compared with the faintest two-thirds (to better match the disturbed/undisturbed split), P is 0.276, but in the sense that the bright galaxies have a slight bias toward high Fr(R) values. In any case, the expected metallicity bias resulting from a difference of 0.4 in galaxy absolute magnitude is very small. The mass–metallicity relation of Tremonti et al. (2004) for galaxies of a few times $10^{10} M_\odot$ predicts a corresponding change of only ∼0.025 dex in log(O/H), highly unlikely to cause any significant effects. Finally, in interacting systems the central metallicity is lowered by the infall of unenriched gas (Michel-Dansac et al. 2008; Ellison et al. 2008; Rupke et al. 2010). This would therefore act opposite to the result we find. It should also be noted that while a study of gas-phase metallicities of the local environments of CCSNe (Anderson et al. 2010) finds a trend favoring SNIIbc in high-metallicity regions, even the highest metallicity environments seem to host a significant fraction of SNII.

It is also possible that stellar rotation (e.g., Heger et al. 2003) and binarity (e.g., Nomoto et al. 1995) could contribute to this effect. It is not clear why the binary fraction should be higher within the disturbed galaxy sample, but it should be noted that the increased densities within these nuclear starburst regions could lead to more massive and denser clusters, within which processes such as stellar mergers and binary interactions would be more prevalent (e.g., Portegies Zwart et al. 2010).

To conclude, our preferred explanation of this central excess of SNIIbc is that the central regions of these disturbed galaxies are hosting starbursts with initial mass functions biased to high stellar masses. Given the small numbers of SNe involved, the uncertain mass limits corresponding to progenitors of different SN types, and the likely role of binarity in determining SN type, it is hard to quantify the implications of this result for the IMF. However, an illustrative calculation can be performed as follows. Under the assumption of a Salpeter IMF, and the (admittedly simplistic) assumptions that CCSNe arise from single stars with masses between 8 and $80 M_\odot$ and that mass alone determines SN type, the relative numbers of SNII and Ibc in the outer regions of undisturbed galaxies ($2.3:1$), if interpreted purely as a change in IMF slope, appears to require a positive index in the IMF slope (formally $x = +0.95$; cf. $-1.35$, assuming that the transition mass is unchanged at $18 M_\odot$). However, we emphasize that this is purely illustrative; all of the assumptions are likely to be in error at some level, and binarity and metallicity effects may play some part in the changes we find.

We note here that we are modifying the conclusions of Anderson & James (2009) in that it is hard to interpret the previously found central SNIIbc excess purely in terms of metallicity effects. However, we note that there is still a marginal central excess of SNIIbc in the undisturbed galaxy sample, indicating some effect of metallicity. Quantifying the
relative sizes of the different effects will be the focus of future studies.

Finally, it is interesting to note that with current research indicating a connection between gamma-ray bursts (GRBs) and type Ic SNe (Woosley & Bloom 2006), recent studies (e.g., Conselice et al. 2005; Wainwright 2007; Fryer et al. 2007) have found that GRB host galaxies show an over-abundance of merging or interacting galaxies compared to other star-forming hosts.

5. CONCLUSIONS

We have analyzed the spatial distribution of 178 CCSNe within a sample of host galaxies with recession velocities less than 6000 km s\(^{-1}\). Host galaxies were classified by eye according to whether they show disturbance due to strong tidal interactions or mergers. The main results are as follows.

1. CCSNe of all types show a strong degree of central concentration in the disturbed galaxies, probably as a result of nuclear starbursts in these galaxies.
2. This central excess is dominated by SNIbc.
3. The SNIbc in disturbed galaxies are more centrally concentrated than the H\(\alpha\) emission.
4. The SNIbc excess cannot easily be explained in terms of metallicity effects, extinction, or central incompleteness of SNe.
5. Our preferred explanation of the SNIbc excess is that the central regions of the disturbed galaxies are dominated by nuclear starbursts with IMFs biased toward high-mass stars, although metallicity, binarity, and stellar rotation may also play a role.

This paper has made use of data provided by the Central Bureau for Astronomical Telegrams. We acknowledge members of staff at the Astrophysics Research Institute, in particular, Sue Percival and David Bersier for their helpful comments and discussion. The authors thank the referee for a constructive and helpful report. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The Isaac Newton Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores
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University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias with financial support from the UK Science and Technology Facilities Council. S.M.H. acknowledges STFC for a research studentship.

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