Abstract. We present \textit{HST} WFPC2 images of Stephan’s Quintet which encompass three interacting galaxies and their associated tidal features. These deep, three-color ($B, V, I$) images indicate recent, massive stellar system formation in various regions within the compact group environment. We have identified star cluster candidates (SCC) both within the interacting galaxies and in the tidal debris. We compare the SCC colors with stellar population synthesis models in order to constrain cluster ages, and compare the pattern of formation of SCC in different regions to the inferred dynamical history of the group.

1. Introduction

The Hickson Compact Groups (HCG; Hickson 1982) are among the densest concentrations of galaxies in the local universe. These high densities combined with relatively low velocity dispersions, $\sigma \sim (2 - 3) \times 10^2$ km s$^{-1}$ (Hickson et al. 1992), make them active sites of strong galaxy interactions. Interactions are believed to initiate bursts of star cluster formation on many scales from dwarf galaxies along tidal tails to massive star clusters, the progenitors of today’s globular clusters. One group in particular, Stephan’s Quintet (SQ; also known as HCG 92), is notable for evidence of multiple interactions.

SQ is comprised of five galaxies: NGC 7317, NGC 7318A and B, NGC 7319 and NGC 7320 (see Fig. 1 for galaxy identifications). Based on multiwavelength observations of the group, NGC 7317 and NGC 7320 show no evidence for recent interactions, unlike the other three galaxies (NGC 7320 is a foreground galaxy). In particular, NGC 7318B shows morphological disruption of spiral structure,
and a long tidal tail extends from NGC 7319. The interactions have resulted in recent and ongoing star formation as evident from $B - V$ (Schombert et al. 1990), Hα (Vílchez & Iglesias-Páramo 1998) and far-infrared (Xu, Sulentic & Tuffs 1999) imaging. Furthermore, in the photometric dwarf galaxy study of Hunsberger, Charlton, & Zaritsky (1996), SQ was identified as hosting the richest known system of tidal dwarf galaxy candidates. From these studies, only the largest star-forming regions were resolved; many of the young stars appeared to be distributed in the diffuse light in the tidal features between the galaxies. High spatial resolution is required to identify star cluster candidates (SCC) which at the distance of SQ ($z = 0.02; d \sim 66h^{-1}$ Mpc) are faint point sources on the Wide Field and Planetary Camera 2 (WFPC2). Hubble Space Telescope (HST) imaging was the obvious next step for investigating the full range in scale of massive star formation structure. Furthermore, with these images we could investigate whether star clusters form in diverse environments from the inner regions of galaxies to tidal debris tens of kiloparsecs from a galaxy center.

2. Observations and Data Analysis

SQ was observed with the HST WFPC2 in two pointings. The first on 30 Dec 1998, encompassed NGC 7318A/B and NGC 7319. The second, on 17 Jun 1999, covered the extended tidal tail of NGC 7319. On both occasions, the images
were once dithered and taken through three wide-band filters: F450W \((B)\), F569W \((V)\) and F814W \((I)\). The exposure times in each field were \(4 \times 1700\) s, \(4 \times 800\) s and \(4 \times 500\) s for \(B, V\) and \(I\), respectively. The data were first processed through the standard HST pipeline. Subsequently, they were cleaned of cosmic rays using the STSDAS task GCOMBINE, followed by the IRAF task COSMICRAYS to remove hot pixels. Fig. 1 shows the \(V\) band image of both fields combined with the regions of interest labeled.

The initial detection of point sources was undertaken using the DAOFIND routine in DAOPHOT (Stetson 1987) with a very low detection threshold. This produced thousands of sources per chip, and we then performed aperture photometry on all sources. Those sources with \(S/N > 3.0\) that appeared in the images at both dither positions were retained. Sources with FWHM > 2.5 or \(\Delta V > 2.4\) were rejected as extended (Miller et al. 1997). Those point sources with \(V - I > 2.0\) are likely foreground stars, and the remaining sources are considered star cluster candidates (SCC). This sample will clearly contain some foreground stars and background galaxies, but the spatial coincidence of most of the sources with the galaxy bulges and tidal features is evidence that many candidates are legitimate SCC. Approximately 150 sources were found in all three filters; they are plotted in the \(B-V\) versus \(V-I\) color-color plot in Fig. 2. In Fig. 3, zoom images of the tidal tail in NGC 7319 and the northern starburst region (NSR) have the SCC marked with circles. For a discussion of the extended sources in the field, see Hunsberger et al. (this proceedings).

3. Discussion

3.1. Dynamical History of Stephan’s Quintet

The diversity of tidal features in SQ is indicative of the complex interaction history in the group. In the dynamical history proposed by Moles, Sulentic, & Márquez (1997; hereafter MSM97), NGC 7320C (out of the frame of Fig. 1 to the northeast) passed through the group a few hundred million years ago stripping NGC 7319 of much of its HI (Shostak et al. 1984) and inducing the extension of the tidal tail. In addition, gas was deposited in the area that is currently the NSR. This first event would have induced star formation in the environs of NGC 7319 and perhaps triggered the observed Seyfert 2 activity in the nucleus.

Two of the four galaxies in Fig. 1, NGC 7319 and NGC 7318A, have radial velocities within 50 km s\(^{-1}\) of 6600 km s\(^{-1}\). A third, NGC 7318B, while apparently interacting with NGC 7318A, has a discordant velocity, \(v = 5700\) km s\(^{-1}\) (Hickson et al. 1992). This discrepancy is inconsistent with the interpretation of NGC 7318B as a foreground galaxy because of the obvious morphological distortion seen in Fig. 1. Instead, in the most recent and ongoing interaction event NGC 7318B is falling into the group for the first time. HI maps of the

\*Dithering entails offsetting the image position by a half-integer pixel amount in both the \(x\) and \(y\) directions in order to increase the effective resolution of the combined image by better sampling the PSF. In this case, we obtained two images in each field and filter.

\†\(\Delta V\) is the difference between the \(V\) magnitudes calculated with two photometric apertures: one with radius 0.5 pix and the other with radius 3.0 pix.
Figure 2. $B-V$ versus $V-I$ color-color plot of star cluster candidates (SCC). The solid line represents the evolutionary tracks for a Bruzual & Charlot (1993) stellar population synthesis instantaneous-burst model (with a Salpeter IMF and solar metallicity). Numbers along the tracks are years. The SCC photometry has not been corrected for Galactic reddening; the models have been reddened with $A_B = 0.49$ (value from the Large Extragalactic Database for Astronomy; Paturel et al. 1997).

In all regions with tidal features or galaxies, we identified SCC. From the simulations of Ashman & Zepf (1992) of merger remnants, we expected to find massive young star clusters in the bulges of NGC 7318A and B, but there we only detected point sources with colors consistent with old globular clusters. This result can be understood if the interaction between NGC 7318A and B is relatively recent, and star formation is just beginning in the outer regions of the galaxies. This picture is consistent with the observations of NGC 7252 (Miller et al. 1997) and the Antennae (Whitmore et al. 1999) which suggest that cluster formation is initiated at large galactic radii and propagates inward over time. In
NGC 7319, we do find young SCC in the disk and bulge, supporting the older interaction scenario for the event which stripped it of its gas and pulled out the tidal tail.

From our images, it is also clear that star clusters can form outside of galaxies. In the NSR, the star formation is occurring \( \gtrsim 20 \) kpc from the bulge of the nearest galaxy. In addition, we discovered several young star clusters in the tidal tail of NGC 7319. In the color-color plot (Fig. 2), there is a clear distinction between the sources associated with NGC 7318B and those in NGC 7319 and its tidal tail. The most recent star formation is occurring in the NSR and the spiral arms of NGC 7318B; ages of some SCC in those regions are at least as young as 5 Myr. Any intrinsic dust extinction would only cause an overestimate of the ages as the reddening vector is approximately parallel to the evolutionary tracks at that point. In addition to the youngest SCC in each region, we also observe a spread of ages from old globular cluster candidates (GCC) with ages \( \tau \sim 10^{10} \) yr to more intermediate-aged SCC, \( \tau \sim 10^8 \) yr. This spread is most apparent in the NSR and along the tidal tail, both regions where extended periods of interaction-induced star formation are reasonable. Furthermore, the
presence of the old GCC in the tidal features suggests they were pulled out of their birth galaxies as a result of the interactions.

4. Conclusions

From *HST* WFPC2 images, we find \( \sim 150 \) SCC in the environs of SQ. SCC are found both within the bulges of each of the galaxies NGC 7318A/B and NGC 7319, and also in tidal features. The ages deduced from \( B-V \) versus \( V-I \) colors of SCC are consistent with the complex interaction scenario outlined by MSM97. Since only old GCC are found in the centers of NGC 7318A/B, this suggests that recent star formation has not yet occurred there. Very young SCC are found along the interaction shock front between the ISM of NGC 7318B and the IGM of SQ supporting the hypothesis that this is a recent event. The spread of ages in SCC found throughout the field is indicative of recurring episodes of interaction-induced star formation.

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Discussion

J. Gallagher: What is the spatial distribution of the cluster colors as compared to colors of the more diffuse debris? This might help in investigating differences between cluster formation versus cluster evolution.

S. G.: In general, the diffuse emission between the galaxies has $B - V$ colors similar to those of the outer regions of spiral disks. More specifically, in the NSR and along the eastern spiral arm of NGC 7318B, the diffuse light has $B - V$ colors between 0.3 and 0.5 (Schombert et al. 1990), as do some regions in the tidal tail. We find young cluster candidates in those regions with similar colors as well as some with $B - V < 0.3$.

T. Böker: In your color-color diagram, there are a handful of “clusters” that are not explained by reddening. Do you have any idea what they are?

S. G.: There does appear to be a group of point sources clumped below the evolutionary tracks on the red end of the $V - I$ axis. I have investigated each of them, and they do not appear to be part of a distinct population. A few of these sources are quite faint in $B$ which could cause some scatter, and there is certainly some contamination from background galaxies and stars.

U. Fritze-von Alvensleben: Where is HI located? Is there any correlation between the absence of HI and the absence of young star clusters?

S. G.: The HI distribution is unusual as most of the gas in the group is outside of the galaxies. There is as much HI as is typically found in an entire spiral galaxy to the south of NGC 7319, including the tidal tail, and a fair amount in the NSB as well (Shostak et al. 1984). We find young SCC in both of those regions. The disk of NGC 7319 is almost entirely lacking in gas, but we find some young SCC candidates in that galaxy, though they are strung along the spiral arms. The bulge of NGC 7318B still has its HI, and does not appear to contain any young SCC.

G. Meurer: Are any of the centers of the galaxies blue? I suspect the reason that you don’t see any nuclear clusters is because the galaxies are too far away hence crowding makes them difficult to distinguish.

S. G.: NGC 7318A and B have similar central colors: $B - V \sim 1.0$ and $V - I \sim 1.2$ that are not particularly blue (though there may be a significant amount of intrinsic reddening). NGC 7319 is bluer with $B - V \sim 0.5$ and $V - I \sim 1.2$; those colors are consistent with the Seyfert 2 activity in the nucleus. The complex structure in the center of each of these galaxies would certainly make detecting a nuclear cluster very difficult. However, we find no young SCC within the inner 2–3 kpc even where the light distribution is smooth. In NGC 7319 we do find young SCC within the bulge of the galaxy.