A Complete Census of Hα Emitters in NGC 6397

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Received 2017 May 9; revised 2017 June 22; accepted 2017 June 27; published 2017 August 4

Abstract
We used a data set of archival Hubble Space Telescope images obtained through the F555W, F814W, and F656N filters to perform a complete search for objects showing Hα emission in the globular cluster NGC 6397. As a photometric diagnostic, we used the $(V – H\alpha)_0$ color excess in the $(V – H\alpha)_0$–$(V – I)_0$ color–color diagram. In the analyzed field of view, we identified 53 Hα emitters. In particular, we confirmed the optical counterpart to 20 X-ray sources (7 cataclysmic variables, 2 millisecond pulsars and 11 active binaries) and identified 33 previously unknown sources, thus significantly enlarging the population of known active binaries in this cluster. We report the main characteristics for each class of objects. Photometric estimates of the equivalent width of the Hα emission line were derived from the $(V – H\alpha)_0$-excess and, for the first time, compared to the spectroscopic measurements obtained from the analysis of MUSE spectra. The very good agreement between the spectroscopic and photometric measures confirms the reliability of the proposed approach to measure the Hα emission. The search demonstrated the efficiency of this novel approach to pinpoint and measure Hα-emitters, thus offering a powerful tool to conduct a complete census of objects with formations and evolutions that can be strongly affected by dynamical interactions in star clusters.

Key words: globular clusters: general – globular clusters: individual (NGC 6397)

1. Introduction

The crowded cores of globular clusters (GCs) are very efficient “furnaces” for generating exotic objects, such as cataclysmic variables (CVs), low-mass X-ray binaries (LMXBs), millisecond pulsars (MSPs), and blue stragglers (see Bailyn 1995). Most of these objects are thought to be the result of the evolution of various kinds of binary systems that originated and/or were hardened by stellar interactions (Davies 2005; Ivanova et al. 2006). The nature and even the existence of binary by-products are strongly related to the cluster core dynamics (Ferraro et al. 2003, 2009, 2015a). Consequently, a complete census of these objects (the formation and evolution of which are strongly affected by dynamical interactions) is crucial in order to trace the dynamical evolution of the parent cluster (Beccari et al. 2006; Ferraro et al. 2012; Lanzoni et al. 2016).

Most of these exotic objects are expected to be potential Hα emitters at the least. LMXBs are binary systems made of a compact object (a stellar black hole or a neutron star (NS)) accreting mass from a low-mass companion through an accretion disk. They are usually bright X-ray sources and, in the case of an NS compact object, they are thought to be the progenitors of MSPs. MSPs form in binary systems containing an NS that first evolved through the LMXB phase and then eventually spun up to millisecond periods by mass accretion from the evolving companion (see e.g., Ferraro et al. 2015b) that, in turn, is expected to become a white dwarf (e.g., Alpar et al. 1982; Lyne et al. 1987; Bhattacharya & van den Heuvel 1991). However, in recent years the numbers of non-degenerate companions has significantly increased (Pallanca et al. 2010, 2013, 2014; Cadelano et al. 2015). Note that the first non-degenerate companion to an MSP in a GC (PSR J1740–5340A) was found by Ferraro et al. (2001) in NGC 6397 (the cluster subject of this paper).

MSPs usually do not have strong Hα excess, since accretion is inhibited by the presence of a strong magnetic field. However, in the cases of transitional-MSPs (T-MSPs), which are thought to be the evolutionary link between LMXBs and MSPs, a significant Hα emission is not unexpected, and it has been indeed confirmed in the case of PSR J1824−2452I in the GC M28 (Pallanca et al. 2013), as well as in the Redback system PSR J1740−5340A in NGC 6397 (Ferraro et al. 2001; Sabbi et al. 2003).

CVs are binary systems in which a white dwarf is accreting material from a main sequence (MS) companion (see Knigge 2012 for a review). From a theoretical point of view, models predict that there should be 60–180 CVs for every $10^5L_\odot$ in an old stellar population (Townesly & Bildsten 2005), most of which should be formed dynamically (Ivanova et al. 2006). Several methods have been proposed to detect candidate CVs (Knigge 2012): (i) studying the variability associated to dwarf nova outbursts; (ii) looking for objects showing bluer colors than MS stars, which is due to the energy released in a hot region close to the white dwarf; (iii) searching for the X-ray emission produced by the accretion onto the compact object; (iv) spectroscopically detecting emission lines. However, none of these methods is able to recover the entire CV population expected and, in most cases, more than one method is needed to properly classify the objects. Beccari et al. (2014) showed that the detection of candidate CVs as sources showing Hα excess emission in GCs can be improved by using a proper combination of broadbands $V$ and $I$ and narrowband Hα imaging. This method was successfully applied in star-forming regions (see De Marchi et al. 2010) and in other clusters (see Pallanca et al. 2013) to identify Hα emitters.

It is worth mentioning that, in addition to the classes of interacting binaries described above, in which the Hα excess is related to the mass transfer process, there are other objects that...
are expected to show Hα emission because of their intense chromospheric activity: these are so-called active binaries (ABs). The two most relevant prototypes of this category of objects are the RS Canum Venaticorum and BY Draconis (BY Dra) binaries. Indeed, a large population of BY Dra-type binaries has been found in NGC 6397 (see Taylor et al. 2001; Cohn et al. 2010).

In this paper we applied the \((V - H_\alpha)_0 - (V - I)_0\) color–color method to identify Hα emitters and to derive a photometric estimate of the Hα equivalent width (EW).

2. The Target Cluster: NGC 6397

In the framework of the study of exotic populations in dense stellar systems, NGC 6397 is an ideal GC to study because its X-ray population is already known and classified. Thanks to deep Chandra imaging of the cluster, Grindlay et al. (2001) detected 25 X-ray sources with \(L_x > 3 \times 10^{29}\) erg s\(^{-1}\) located within 2′ from the cluster center. In a more recent work, Bogdanov et al. (2010) identified 79 Chandra X-ray sources that lie within the half-mass radius \(r_h = 2'.33\) Harris 1996): 15 are CVs, 42 are ABs, one is a radio-detected MSP, and one is a candidate MSP (Cohn et al. 2010). The comparison between the MSP and CV populations of NGC 6397 and 47 Tuc shows that the CV to MSP ratio is \(~10\) times larger in NGC 6397, thus suggesting a dichotomy of compact objects and binary production in the two clusters. NGC 6397 has overproduced CVs (for its mass), perhaps because of two-body captures during core collapse, while its relatively lower MSP production might be due to a lower NS retention or original fraction due to differences in the cluster’s initial mass functions, in turn due to their very different metallicities (Grindlay et al. 2001).

The CV population of NGC 6397 has been identified using different methods: CVs 1–3 were originally identified in an HST Hα survey (Cool et al. 1995), CVs 4–5 were found via optical variability or as counterparts to ROSAT HRI sources (Cool et al. 1998; Grindlay 1999), CVs 6–8 were discovered in a deeper follow-up HST Hα survey (Grindlay et al. 2001), CV9 has been identified on the basis of its Chandra spectrum, and the remaining CVs have been detected as Chandra X-sources (Bogdanov et al. 2010).

A spectroscopic confirmation through hydrogen and helium lines has been obtained for four objects (CVs 1–4; Grindlay et al. 1995; Edmonds et al. 1999). All of these CVs show He II \(\lambda 4686\), a line seen almost exclusively in magnetic CVs and nova-like variables. For CV2 and CV3 the authors also observed nova-like eruptions, which are unexpected for magnetic CVs, since the magnetic field should prevent the disk instability that leads to the nova phenomenon.

Variability has been detected in CVs 1–9, and in two cases it has been found to be particularly strong: CV2 shows a variability of at least 2.7 mag, and CV3 is seen 1.8 mag brighter in eruption than in quiescence (Shara et al. 2005). On the other hand, CV1 and CV6 were identified as eclipsing CVs by Kaluzny et al. (2003). The light curves of both of them exhibit two distinct minima per orbital period and they seem to be dominated by ellipsoidal variations. The accretion rate in CV6

![Figure 1. Reddening-corrected, optical color–magnitude diagram of NGC 6397. The black line indicates the location of the best-fit isochrone (age = 13.5 Gyr, [Fe/H] = −2.03, [α/Fe] = 0.4; Richer et al. 2008), assuming a reddening of \(E(B − V) = 0.18\) and a distance modulus \((m − M)_0 = 12.01\). The location of stars with 0.2, 0.5 and 0.75 \(M_\odot\) masses are labeled and marked with the arrows.](image-url)
has been roughly constant over the observing seasons 2002–2004 (Kaluzny et al. 2006).

Cohn et al. (2010) showed the location of the CV candidates in the color–magnitude diagrams (CMDs) and suggested that there is an evolutionary sequence from young, bright CVs, to old, faint ones. The optical emission of the six brightest CVs appears to be dominated by a relatively massive secondary, while that of the faint CVs is mainly due to the white dwarfs, with very little contribution from a very low-mass secondary.

Cohn et al. (2010) reported on the detection of 42 candidate ABs, 25 of which lie within the field covered with the data used in this work. Most of them draw a relatively homogeneous binary sequence alongside the MS (Cohn et al. 2010), and according to Taylor et al. (2001) they are likely BY Dra objects.

In this paper we applied the selection method of Hα emitters commonly used in star-forming regions (De Marchi et al. 2010) and recently applied to GCs (Pallanca et al. 2013; Beccari et al. 2014) as a tool to both identify exotic objects and derive a photometric estimate of the EW (pEW) of the Hα emission.

3. Observations and Data Reduction

The data used in this work (GO 7335 PI Grindlay) consists of 88 images obtained with the Wide Field Planetary Camera 2 (WFPC2) in the broad F555W and F814W bands and the narrow F656N filter (hereafter V, I and Hα, respectively).

We analyzed the entire set of images through a standard pointspread function (PSF) fitting procedure by using DAOPHOT/ALLFRAME (Stetson 1987). In short, we calculated a PSF model on each image using approximately 50 isolated and unsaturated stars. We then used the DAOPHOT/MONTAGE2 routine to stack all of the V and I images together. In this way we obtained four very deep and very high signal-to-noise ratio (S/N) images (one for each CCD of the WFPC2 detector), cleaned of cosmic rays and detector blemishes. We extracted a list of stellar sources from these reference images and used it as an input master list of ALLFRAME (Stetson 1994), which simultaneously determines the star brightness in all frames. The magnitude of each star in each band was then obtained as the average of at least four measurements, while the standard deviation of the repeated measures was taken as photometric error. We calibrated the WFPC2 magnitudes into the VEGA-MAG system using the standard recipe and zeropoints reported in Holtzman et al. (1995). Finally, we de-reddened all of the observed magnitudes by assuming a color excess $E(B - V) = 0.18$ (Gratton et al. 2003; Richer et al. 2008).

We show in Figure 1 the reddening-corrected $V_0$ versus $(V - I)_0$ CMD obtained from the WFPC2 photometric catalog (gray points). The cluster’s stars are sampled from the bottom of the red giant branch down to ~7 mag below the MS turn-off ($V_0 \sim 16.2$). The best-fit isochrone (Dotter et al. 2008), obtained for an age = 13.5 Gyr, a metallicity [Fe/H] = −2.03 and [$\alpha$/Fe] = 0.4 (Richer et al. 2008), and assuming a distance modulus $(m - M)_0 = 12.01$ (Gratton et al. 2003), is also shown in Figure 1 (solid line). The isochrone has been used to convert the sampled magnitudes into stellar masses. As shown in Figure 1, we are able to sample the MS stars from 0.75 $M_\odot$.
corresponding to the mass of stars at the turn-off) down to $0.2 \, M_\odot$ at the bottom of the MS.

Finally, we transformed the relative stellar positions into absolute right ascension (R.A.) and declination (decl.) using more than 300 stars in common with a photometric catalog (Ferraro et al. 2001) from ground-based images obtained with the Wide Field Imager (WFI) at the 2.2 m telescope at La Silla. This allowed us to obtain a global astrometric accuracy of $0^\prime\,3$ in both R.A. and decl. It is worth noticing that the same astrometric accuracy allowed Ferraro et al. (2001) to identify the optical counterpart of the MSP J1740$-$5340 in the same HST WFPC2 data set that is used in this paper.

4. Selection of Hα Emitters and EW Measure

4.1. Photometric Approach

We used the method described in De Marchi et al. (2010) and recently applied to GCs by Beccari et al. (2014) and Pallanca et al. (2013) in order to identify all of the objects showing Hα excess in the WFPC2 field of view. In Figure 2 we show as gray points the position of all of the stars with magnitude fainter than the MS turn-off in the $(V - H\alpha_0)$ versus $(V - I)_0$ color--color diagram. Note that with this color combination we can both reproduce the continuum for different spectral types and provide a good estimate of the Hα emission, with the Hα line contribution to the V band being negligible. As expected, the vast majority of MS stars show very low (if any) Hα excess emission. As a consequence, in the $(V - H\alpha_0)$ versus $(V - I)_0$ plane they define a very narrow sequence, which empirically indicates the locus of stars with no Hα emission. The conversion of the $(V - I)_0$ colors into stellar temperatures and spectral types indicated in the figure is done using the atmospheric model of Bessell et al. (1998; gray triangles). To first select objects with Hα excess and then estimate the pEW of the emission, we calculated a reference line for the stars not showing Hα excess that is defined as the median $(V - H\alpha_0)$ color of stars with a combined photometric error (computed as \( \sigma_{V-H\alpha_0} = \sqrt{\sigma^2_v + \sigma^2_{H\alpha}} \)) smaller than 0.05 mag. It is important to note that the empirical relation (gray solid line in the Figure 2) agrees very well with the theoretical one from the atmospheric model of Bessell et al. (1998). For each source, we measured the “color” difference $(\Delta(V - H\alpha_0))$ between the observed $(V - H\alpha_0)$ color and the value of $(V - H\alpha_0)$ measured along the reference line at the source $(V - I)_0$. We then selected as candidate Hα emitters those objects with $(\Delta(V - H\alpha_0))$ that is at least five times larger than the source intrinsic error (see Figure 3). The use of such a conservative threshold guarantees avoiding the selection of objects showing a “fake” color excess, which is actually due to a large intrinsic photometric error. We performed a visual inspection of each candidate Hα emitter onto the stacked images in order to exclude objects possibly contaminated from close saturated stars. This procedure allowed us to reject almost half of the initially selected candidates.
We also accepted as bona-fide Hα emitters the objects with $(V - \text{H} \alpha)_0$ color excess four times larger than the intrinsic error, but falling within 0.5 from the nominal position of an X-ray source. In this way we added four more objects to the previous selection (see stars marked by asterisks in Figures 3 and 4). Following this approach, we identified 53 candidate Hα emitters: their coordinates and magnitudes are listed in Table 1, and their positions in the $V - V - \text{I}_0$ CMD are shown in Figure 5.

We then reported the position of these objects in the color–color diagram (Figure 4), the ideal plane to directly measure the pEW of the emission. For all of the selected bona-fide Hα emitters, we derived a pEW estimation of the Hα emission line following Equation (4) in De Marchi et al. (2010): $\text{pEW} = \text{RW} \times [1 - 10^{-0.4 \times (\Delta \text{H}_{\alpha})}]$, where RW is the rectangular width of the filter in Å units, which depends on the specific characteristics of the filter (see Table 4 in De Marchi et al. 2010). The obtained values are listed in Table 1 and reported in Figure 6 as a function of the $(V - I)_0$ color. The eight faintest (with $V_0 > 22$) objects without an X-ray counterpart, for which the photometric errors are larger than $\sigma_{(V - \text{H} \alpha)_0} > 0.05$ mag, are considered “low-confidence candidates” and for this reason they are plotted as open circles in Figures 3–6.

4.2. Comparison with MUSE

Very recently Husser et al. (2016) presented the spectroscopic analysis of more than 12,000 stars in NGC 6397 observed with the VLT-MUSE, a panoramic integral-field spectrograph able to acquire low-resolution spectra ($R = 2000–4000$, from the bluest to the reddest wavelengths) in the range 0.465–0.93 μm (Bacon et al. 2014). While most of the Hα emitters selected through our photometric strategy fall below the MUSE detection threshold, we were able to retrieve the spectra of 20 sources in common with our photometric catalog. They have been used to obtain a spectroscopic estimate of the Hα EW (sEW) for a direct comparison with our photometric values (pEWs).

From the best-fit isochrone, we assigned a temperature and a surface gravity to each target. These have then been used to calculate a synthetic spectrum with the SYNTHE code developed by R. L. Kurucz. After the convolution with a Gaussian profile, needed to reproduce the spectral resolution of MUSE, we determined the radial velocity of each target through cross-correlation (by using the iraf task fxcor) with the synthetic spectrum in the Calcium triplet region, and we reported the observed spectra to the rest frame. In the following comparison with MS stars, the shift to the rest frame is fundamental because, being members of binary systems, the Hα emitters can have a radial velocity significantly different from GC systemic velocity and variable along orbital phase. We then adopted the same approach to analyze a sample of MS stars with comparable temperature and gravity and, once this was reported to the zero velocity rest frame, we built a reference median template through the IRAF task scombine. Finally, because for most objects the Hα line in the atmosphere of the Hα emitters appears just as a less-absorbed feature with respect to what is observed in unperturbed stars with similar
| ID   | R.A. J2000  | Decl. J2000 | V0  | I0  | Hα0  | pEW | sEW | B10 | G01 | K06 | T01 | H16 |
|------|-------------|-------------|------|-----|------|-----|-----|-----|-----|-----|-----|-----|
| CV1  | 265.1733338 | −53.6720901 | 17.91| 17.07| 16.51| 24.3 ± 0.4| 14.0 ± 1.7–5.0 ± 0.5| 21.1 ± 1.3–4.5 ± 0.4| U23 | CV1 | V12 | 10639 |
| CV2  | 265.1762738 | −53.6746139 | 19.14| 18.07| 17.64| 21.0 ± 0.4| 30.2 ± 1.3| U19 | CV2 | V34 |     |
| CV3  | 265.1777106 | −53.6720105 | 17.83| 17.46| 16.73| 29.1 ± 0.3| 71.7 ± 2.8| U17 | CV3 | V33 |     |
| CV4  | 265.1742981 | −53.6725857 | 19.70| 18.65| 17.26| 90.4 ± 1.0| 106.7 ± 1.7| U21 | CV4 |     |     |
| CV5  | 265.1737722 | −53.6747031 | 20.68| 19.62| 18.26| 87.4 ± 1.4| U22 | CV5 |     |     |     |
| CV6  | 265.2040901 | −53.6634800 | 19.27| 18.33| 18.01| 15.2 ± 0.4| 14.2 ± 3.3–23.3 ± 3.3| U10 | CV6 | V13 | 8919 |
| CV7  | 265.1907295 | −53.6782007 | 23.78| 22.94| 22.23| 32.5 ± 5.5| U11 | CV7 |     |     |     |
| MSP-A| 265.1859047 | −53.6782108 | 16.43| 15.68| 15.66| 3.2 ± 0.2| 3.0 ± 0.1| U12 | V16 | BY (WF4-1) | 4991 |
| MSP B| 265.1775326 | −53.6743174 | 16.05| 15.12| 15.11| 4.2 ± 0.2| 3.9 ± 0.2| U18 | V31 | BY (PC-8) | 5596 |

1. 265.1826286 −53.6782726 17.80 17.07 17.05 3.0 ± 0.2 N.M. 5213 |
2. 265.1792970 −53.6770140 18.27 17.47 17.50 2.2 ± 0.3 N.M. 5438 |
3. 265.1669335 −53.6582910 18.30 17.47 17.51 2.3 ± 0.3 N.M. 14481 |
4. 265.1869772 −53.6735069 18.31 17.49 17.54 1.8 ± 0.2 N.M. 9678 |
5. 265.1721989 −53.6682152 18.93 17.99 18.06 2.0 ± 0.3 N.M. 10681 |
6. 265.1743181 −53.6746601 19.45 18.30 18.41 2.1 ± 0.3 N.M. 5917 |
7. 265.2040749 −53.6776261 19.46 18.71 18.70 2.9 ± 0.3 N.M. 8966 |
8. 265.1684970 −53.6574071 19.56 18.49 18.50 4.6 ± 0.5 N.M. 10841 |
9. 265.1835070 −53.6748396 20.33 18.89 19.03 3.4 ± 0.4 N.M. 10230 |
10. 265.1982481 −53.6658034 20.37 19.04 19.14 3.7 ± 0.4 N.M. 10564 |
11. 265.2119807 −53.6617568 20.75 19.51 19.58 3.8 ± 0.5 N.M. 10681 |
12. 265.1830621 −53.6782471 20.81 19.42 19.53 3.9 ± 0.5 N.M. 5917 |
13. 265.1763986 −53.6829417 20.96 19.78 19.68 8.9 ± 0.9 N.M. 8966 |
14. 265.2131393 −53.6744206 21.09 19.83 19.86 5.2 ± 0.8 N.M. 10841 |
15. 265.2074017 −53.6694465 21.23 19.79 19.91 3.9 ± 0.6 N.M. 10230 |
16. 265.1715432 −53.6897092 21.36 19.94 19.97 6.6 ± 0.9 N.M. 10564 |
17. 265.1748629 −53.6915474 21.37 20.31 20.27 5.9 ± 0.8 N.M. 10681 |
18. 265.1691896 −53.6571696 21.38 19.90 19.85 10.0 ± 1.0 N.M. 10841 |
19. 265.1848957 −53.6763541 21.39 19.92 20.05 4.1 ± 0.7 N.M. 10681 |
20. 265.2063740 −53.6645454 21.39 20.06 20.08 6.1 ± 0.7 N.M. 10564 |
21. 265.2089110 −53.6693385 21.45 20.00 20.02 7.1 ± 0.7 N.M. 10841 |
22. 265.1824425 −53.6817866 21.48 19.89 19.99 6.1 ± 0.9 N.M. 10564 |
23. 265.1929464 −53.6694839 21.69 20.16 20.19 7.7 ± 1.1 N.M. 10841 |
24. 265.2055337 −53.6651658 21.69 20.20 20.26 6.5 ± 0.9 N.M. 10564 |
25. 265.1900309 −53.6602075 21.91 20.32 20.41 6.1 ± 1.1 N.M. 10841 |
26. 265.2121746 −53.6743002 22.08 20.52 20.56 7.8 ± 1.1 N.M. 10564 |
27. 265.1810287 −53.6956426 22.37 21.09 20.88 13.9 ± 1.8 N.M. 10841 |
28. 265.1688267 −53.6575723 22.43 20.73 20.38 25.0 ± 2.6 N.M. 10564 |
29. 265.1888864 −53.6906782 22.57 20.71 20.74 11.5 ± 1.6 N.M. 10841 |
30. 265.1739928 −53.6769901 22.77 20.60 20.61 19.8 ± 2.7 N.M. 10564 |
physical parameters, we divided the target spectra by the reference template, in order to isolate the emission component, and we measured the sEW through a Gaussian fit. In some cases the line profile was asymmetric (likely due to $\text{H}_\alpha$ emission coming from different regions of the system; e.g., see Sabbi et al. 2003) and a minor, secondary Gaussian component was used in the fit.

In order to estimate the uncertainties in the sEW measures we performed Monte Carlo simulations. We first simulated five templates with different $\text{H}_\alpha$ sEWs (1 Å, 3 Å, 5 Å, 10 Å, and 50 Å). For each template we built a set of simulated spectra with variable $S/N$, ranging from 5 to 50 in steps of 5. Then we ran an automatic procedure to measure the sEW in each set of simulated spectra. Thus the dispersion of the sEW measures was derived as a function of both the measured sEW and the spectrum $S/N$. This grid of values was used to derive the uncertainty of each $\text{H}_\alpha$ sEW measured in a spectrum of a given $S/N$. The values obtained are reported in Table 1.

For CV1 and eight ABs, two different MUSE spectra are available in the Husser et al. (2016) data set and we thus obtained two measures. For the eight ABs, the two values agree with each other within 1σ uncertainties. In the case of (the main component of) CV1, we obtain 14 Å and 27.1 Å, while Edmonds et al. (1999) found 21 Å from HST spectroscopy. These differences are likely due to the intrinsic variability of the emission and the time difference between the observations.

Table 1 (Continued)

| ID | R.A. J2000 | Decl. J2000 | $V_0$ | $I_0$ | $H_\alpha$ | pEW | sEW | B10 | G01 | K06 | T01 | H16 |
|----|------------|-------------|------|------|-----------|-----|-----|-----|-----|-----|-----|-----|
| 31 ? | 265.1918767 | $-53.6491195$ | 22.79 | 21.12 | 20.88 | 19.6 ± 2.4 |
| 32 ? | 265.1921196 | $-53.6776013$ | 23.26 | 21.22 | 20.94 | 30.2 ± 3.1 |
| 33 ? | 265.1872843 | $-53.6910091$ | 23.58 | 21.69 | 21.42 | 24.7 ± 3.6 |

Note. From left to right: source name, absolute coordinates, de-reddened magnitudes, photometric EW, spectroscopic EW (more than one value is reported if the line profile has been fitted by two Gaussians; a second raw is added when more that one spectrum is available; the values marked by an “E” are the measures from Edmonds et al. 1999); and N.M. means that although the spectra are available, it has been impossible to measure the EW, list of IDs in papers available in the literature: B10—Bogdanov et al. 2010; G01—Grindlay et al. 2001; K06—Kaluzny et al. 2006; T01—Taylor et al. 2001; H16—Husser et al. 2016. In the first section of the table we report all of the objects that have an X-ray counterpart and divide them into CVs, MSPs, and ABs. The four objects marked by the asterisk correspond to those stars selected although they were slightly below the imposed threshold (see Section 4.1 for more details). The eight objects marked by the ? correspond to the faintest stars for which the classification is uncertain due to their large photometric errors.

Figure 5. CMD location of object with $\text{H}_\alpha$ excess. The black crosses and dots correspond to the objects with and without the X-ray counterpart, respectively. As in previous figures, the faintest objects ($V > 22$), for which the classification is uncertain because of the large photometric errors, are plotted as open circles. The names of sources with X-ray counterparts are reported for clarity.
All of the sEWs thus obtained are listed in Table 1, where we also report the values quoted in Table 1 of Edmonds et al. (1999) for CVs 1–4. As shown in Figure 7, we find a general good agreement between the photometric and the spectroscopic measurements of the Hα EW for the stars in common with the MUSE catalog. The largest discrepancies are found for CVs (note that the axes in the figure are logarithmic), and can again be explained by the intrinsic variability of their Hα emission and by taking into account the fact that the WFPC2 and the MUSE observations of the cluster have been performed in very different epochs (the photometric and the spectroscopic data were acquired in 1999 April and 2014 July, respectively). This comparison is critical since it provides the first direct test of the fact that a combination of broadband with narrowband Hα imaging allows us to obtain reliable photometric measurements of the EW of stars showing Hα excess. This is particularly critical in regions where severe stellar crowding or target faintness prevents the gathering of reliable spectroscopic data.

5. Discussion

Using the selection criteria described in the previous section we found 53 objects with Hα excess. Through cross-correlation with catalogs of peculiar sources in this GC (i.e., X-ray sources and variable stars; Cohn et al. 2010 and Kaluzny et al. 2003, respectively) we were able to find associations with previously known objects. In particular we found that 20 Hα emitters (7 CVs, 2 MSPs and 11 ABs) have an X-ray counterpart. Moreover, eight objects (among the brightest) were identified as variable stars and nine sources were previously classified as BY Dra-type binaries. The remaining 33 candidates are new sources. We stress here that the eight faintest objects (without a X-ray counterpart) are however considered uncertain because of the large photometric errors. See Table 1 for a summary.

All of the seven detected CVs show a pEW larger than 15 Å. In particular, they appear to be divided in two groups: CV4 and CV5 have pEW larger than 80 Å, while CV1, CV2, CV3, CV6, and CV7 show an average Hα excess (pEW ~ 25 Å). Such a dichotomy is suggestive of a different evolutionary state (Pallanca et al. 2013) or a different accretion state (likely depending on the nature of the compact object). In fact, even if they are classified as CVs, we cannot definitely rule out the hypothesis that some of them could be T-MSPs, similar to PSR J1023+0038 and PSR J1227−4853 (Stappers et al. 2014; Roy et al. 2015). In the CMD (see Figure 5) they are located both on the left and on the right side of the MS. This evidence confirms that the CMD position alone (e.g., a color bluer than the MS) cannot be exhaustively used to select a complete sample of CVs, and that the pEW that we can measure with the observational method described in this paper is indeed critical.

Interestingly, all 11 of the ABs found in our catalog show a pEW smaller than 4 Å and lie on the sequence of binary systems observed on the red side of the MS (see Figure 5). Note also that while they all have known X-ray counterparts, only seven were previously identified in optical bands as possible BY Dra binaries (Taylor et al. 2001; see also Table 1), thus suggesting that the Hα selection method allowed us to detect four more ABs (~50% more) with respect to the optical variability study.

Figure 6. Estimated photometric EW of the emission, as a function of the color index representative of the spectral type. The symbols are as in the previous figure. The names of known CVs are reported for clarity.
We performed a Kolmogorov–Smirnov test comparing the radial distributions of X-ray CVs, X-ray ABs, and MS stars. We found that both the CVs and the ABs are more concentrated than MS stars (see Figure 8). In particular, the probability that they are extracted from the same parent population of MSs is only of the order of 0.1%–0.2%, while the radial distributions of ABs is compatible with that of CVs with a probability of 28%. Finally, the two MSPs (the radio-known U12 and the candidate U18) have a small pEW, slightly larger than the values measured for the ABs. This is a further confirmation that source U18 is very similar to U12 (PSR J1740−5340A) and that it fits well within the scenario already proposed by Bogdanov et al. (2010), who found that its X-ray and optical properties are consistent with those of a binary containing a rotation-powered pulsar wind interacting with material from the secondary star.

Among the sources without an X-ray counterpart, only one object is known in the literature and it is classified as a possible BY Dra-type binary (star number 10 in Table 1). Eleven of the Hα emitters with no X-ray counterpart have a pEW < 4 Å and in the CMD they are located on the cluster binary sequence. The two MSPs are both located below the Sub Giant Branch and have a pEW of emission slightly larger than that of the ABs. The CVs are mostly out of canonical sequence in the CMD, both on the left and on the right side of the MS, and they have a significantly large Hα emission (pEW > 15 Å), suggesting that for these objects the source of emission is an accretion process instead of chromospheric activity (as is likely for ABs). The CVs seem to have two different regimes of accretion. In particular, CV4 and CV5 are characterized by a strong Hα, similar to the peculiar T-MSP J1824−2452I in M28 (Pallanca et al. 2013). We also detected several objects with no X-ray counterparts: these objects can be ABs or interacting binaries. In this paper we used an innovative method to estimate the EW through photometric observations. The derived values have been found to nicely correlate with the spectroscopic measurements, thus confirming the reliability of the photometric approach. Such a method allows us to detect new objects with Hα excess and, in principle, to measure the emission EW also from objects that are too faint to be the target of spectroscopic observations.

6. Summary and Future Perspectives

By using a set of high-resolution images of the central region of the GC NGC 6397, acquired through the V, I, Hα filters, we identified 53 objects with Hα excess. Among them there are 20 X-ray sources: 7 CVs, 11 ABs, 1 radio MSP, and 1 candidate MSP. In particular, all of the ABs have a pEW smaller than 4 Å and in the CMD they are located on the cluster binary sequence. The two MSPs are both located below the Sub Giant Branch and have a pEW of emission slightly larger than that of the ABs. The CVs are mostly out of canonical sequence in the CMD, both on the left and on the right side of the MS, and they have a significantly large Hα emission (pEW > 15 Å), suggesting that for these objects the source of emission is an accretion process instead of chromospheric activity (as is likely for ABs). The CVs seem to have two different regimes of accretion. In particular, CV4 and CV5 are characterized by a strong Hα, similar to the peculiar T-MSP J1824−2452I in M28 (Pallanca et al. 2013). We also detected several objects with no X-ray counterparts: these objects can be ABs and or interacting binaries.

In this paper we used an innovative method to estimate the EW through photometric observations. The derived values have been found to nicely correlate with the spectroscopic measurements, thus confirming the reliability of the photometric approach. Such a method allows us to detect new objects with Hα excess and, in principle, to measure the emission EW also from objects that are too faint to be the target of spectroscopic observations.
Note that the proposed selection method could play a fundamental role in the detection of T-MSPs. For example, the two known field T-MSPs were initially misidentified as magnetic CVs (Bond et al. 2002; Butters et al. 2008). In particular, during their life T-MSPs likely change the amount of Hα excess significantly (i.e., during the quiescent state PSR J1824−2452I shows a pEW of a few Å, as the ABs, while during the burst phase it is characterized by strong emission, even larger than some CVs).

An important step forward will be to obtain similar data sets in different epochs in order to identify objects (such as T-MSPs, active LMXB, and CVs) that are significantly changing their status along time. Moreover, coordinated photometric and spectroscopic observations planned at the same time would be important to further test the correlation between pEW and sEW without the bias of intrinsic variability of accretion.

We thank the anonymous referee for the careful reading of the manuscript and useful comments. C.P. warmly acknowledges the support of the ESO Visitor Program. The research leading to these results has received funding from the European Community’s Seventh Framework Programme (/FP7/2007-2013/) under grant agreement No. 229517, and is based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Institute. STScI is operated by the association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555.

Facilities: ESO (WFI), HST (WFPC2).

Figure 8. Cumulative radial distribution of different populations. In the top-left part of the plot the legend of different populations is reported. The shaded gray area represents the core radius (5′′5; Cohn et al. 2010). The X-ray CVs and ABs, as well as the candidate ABs, are significantly more concentrated than MSs.

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