High-resolution \(H\alpha\) imaging of the northern Galactic plane and the IGAPS image database

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ABSTRACT

The INT Galactic Plane Survey (IGAPS) is the merger of the optical photometric surveys IPHAS and UVEX based on data from the Isaac Newton Telescope (INT) obtained between 2003 and 2018. It captures the entire northern Galactic plane within the Galactic coordinate range \(|b| < 5^\circ\) and \(30^\circ < l < 215^\circ\). From the beginning, the incorporation of narrow-band \(H\alpha\) imaging has been a unique and distinctive feature of this effort. Alongside a focused discussion of the nature and application of the \(H\alpha\) data, we present the IGAPS world-accessible database of images for all five survey filters, \(i, r, g, U_{\text{BGO}},\) and narrow-band \(H\alpha\), observed on a pixel scale of 0.33 arcsec and at an effective (median) angular resolution of 1.1–1.3 arcsec. The background, noise, and sensitivity characteristics of the narrow-band \(H\alpha\) filter images are outlined. Typical noise levels in this band correspond to a surface brightness at full \(r\)-band magnitude of \(\sim 1\) arcsec$^2$. Illustrative applications of the \(H\alpha\) data to planetary nebulae and Herbig-Haro objects are outlined, and, part of a discussion of the mosaicking technique, we present a very large background-subtracted narrow-band mosaic of the supernova remnant Simeis 147. Finally, we lay out a method that exploits the database via an automated selection of bright ionised diffuse interstellar emission targets for the coming generation of wide-field massive-multiplex spectrographs. Two examples of the diffuse \(H\alpha\) map output from this selection process are presented and compared with previously published data.

Key words. surveys – astronomical databases: miscellaneous – ISM: general – HII regions – planetary nebulae: general – ISM: supernova remnants

1. Introduction

The stellar and diffuse gaseous content of the Galactic plane continues to be a vitally important object of study as it offers the best available angular resolution for exploring how galactic disc environments are built and how they operate and evolve over time. For studies of the diffuse interstellar medium (ISM), the optical offers \(H\alpha\) – emission in this strong transition is the pre-eminent tracer of ionised gas. By definition, the ISM is an extended object that must involve investigation by means of imaging data.
Our purpose here is to present and describe a newly complete resource that enables this style of astronomy, specifically within the gas- and dust-rich northern Galactic plane.

There is a history, stretching back over the last century, of comprehensive surveying of the optical night sky. Until around 1990, much of the wide-area effort depended on photographic emulsions on glass as detectors (e.g. the Palomar, ESO, and UK-Schmidt sky surveys, described by Lund & Dixon 1973; West 1974; Morgan et al. 1992, respectively). The last 30 years have seen a switch to digital detectors that has brought with it the benefits of linearity and increased dynamic range, paving the way for increasingly precise photometric calibration. Thanks to this change and the advance of data science, the community now has access to a number of wide-area broadband surveys offering images at approximately arcsecond angular resolution and point-source catalogues (e.g. SDSS, Pan-STARRS, DECaPS, and Skymapper; see Alam et al. 2015; Chambers et al. 2016; Schlafly et al. 2018; Wolf et al. 2018).

Wide-area narrow-band Hα imaging, our main focus here, has generally been pursued separately from broadband work (most notably VTSS, SHASSA, and WHAM; see Dennison et al. 1998; Gaustad et al. 2001; Haffner et al. 2003). Finkbeiner (2003) merged these surveys into a single map that covers much of the sky, albeit at an angular resolution limited to 6 arcmin. Inevitably, most Hα nebulous is concentrated in the Galactic plane, along with most of the Galaxy’s gas, dust, and stars. Within the plane, the angular resolution needs to be better than this to begin to resolve individual clusters and HII regions that show structure on the sub-arcminute scale. The UK Schmidt Hα Survey (SHS; Parker et al. 2005), based on photographic film, has met this challenge in the southern Galactic plane with imaging data of a resolution approaching 1 arcsec. Before the imaging presented here began to be collected, the same could not be said for the plane in the northern hemisphere.

The focus of this paper is full coverage of the plane of the northern Milky Way via digital narrow-band Hα imaging at ~1 arcsec angular resolution obtained from 2003 up to 2018 using the Wide Field Camera (WFC) on the Isaac Newton Telescope (INT) in La Palma. We showcase the properties of the Hα images and point out different modes of exploitation, past, present, and future. Alongside this we also present the INT Galactic Plane Survey (IGAPS) five-filter image database. IGAPS is the cross-calibrated merger of the two Galactic plane surveys, IPHAS (INT Photometric Hα survey of the northern Galactic plane; Drew et al. 2005) and UVEX (UV-Excess survey of the northern Galactic plane; Groot et al. 2009). Together, these surveys have offered a new mix of narrow-band Hα alongside four broad bands, spanning the optical. The IPHAS filters were r/i/Hα, while the UVEX survey incorporated a repeat in r and g/U_2AO observations. The total IGAPS footprint is a 1850 sq. deg. strip along the Galactic plane defined on the sky in Galactic coordinates −5° < b < +5° and 30° < l < 215°. Monguió et al. (2020) have recently presented the merged and calibrated IGAPS point-source catalogue of aperture photometry derived from the IPHAS and UVEX surveys. The focus of this study is on the extraction of stellar photometric data. It did not take on the characterisation of the extended ionised emission traced by the Hα images. This is the partner paper in which this missing piece is put in place.

Here we outline the world-accessible database of IGAPS images that we have set up to hold the Hα (and broadband) data. It is reached via a website that also provides access to the Monguió et al. (2020) point-source catalogues. The imagery we have archived incorporates all IPHAS and UVEX observations, including a minority that did not meet all the desired survey quality criteria. The majority of the included images benefit from the uniform photometric zero points computed by Monguió et al. (2020) when building the IGAPS point-source catalogue.

The structure of the paper is as follows. In Sect. 2 we summarise the relevant features of IGAPS data and our methods as well as the contents of the image database. This is followed by an outline of the search tool available for querying the database (Sect. 3). Attention then switches to our main focus: the properties and application of the narrow-band Hα + [NII] imagery. Section 4 sets the ball rolling with an overview of the sensitivity and the nature of the background captured in the narrow-band filter. We then go on, in Sect. 5, to highlight two contrasting examples of its exploitation for the science of diffuse nebulae (planetary nebulae and Herbig-Haro objects). A discussion of techniques for mosaicking the Hα data then follows (Sect. 6). Looking to the near future of massively multiplexed optical spectrographs, we present a method for automated searching of the IGAPS image database for high Hα surface brightness non-stellar diffuse-ISM spectroscopic targets (Sect. 7). To round off, we show two contrasting examples of the output from the automated search in Sect. 7.4.

2. Description of the image database

A series of papers (Drew et al. 2005; González-Solares et al. 2008; Groot et al. 2009; Barentsen et al. 2014; Monguió et al. 2020) has already described the survey data acquisition and pipelining. So here it is only necessary to repeat pertinent details.

The camera used, the INT’s WFC, is a mosaic of four charge-coupled devices (CCDs) arranged in an L shape with a pixel size of 0.33 arcsec pixel−1. Each CCD images a sky region of roughly 11 × 22 sq. arcmin, giving a total combined field per exposure of approximately 22 sq. deg. The five filters used – U_2AO, g, r, i, and a narrow-band Hα – have central wavelengths of 364.0, 484.6, 624.0, 774.3, and 658.6 nm, respectively. Despite the filter’s different naming, the U_2AO transmission curve quite closely resembles that of Sloan r (Doi et al. 2010). We shall refer to the narrow-band filter as the Hα filter throughout this work, but we note for completeness that the 95 Å bandpass also captures the [NII] 654.8, 658.4 nm forbidden lines typical of HII-region emission. The numbers of CCD images per filter in the repository are listed along with other performance parameters in Table 1. UVEX and IPHAS r band observations are distinguished by labelling them r_U and r_IPH, respectively.

IPHAS and UVEX shared the same footprint and set of pointings, such that the northern Galactic plane was covered via 7635 WFC pointings, tessellating the survey area with, typically, a small overlap. In addition, each field was observed again, and usually around 5 min later, at an offset of +5 arcmin in RA and +5 arcmin in Dec in order to fill in the gaps between the CCDS and also to minimise the effects of bad pixels and cosmic rays. As a result, almost all locations in the northern plane have been imaged twice in either survey. The presence of the r band in both surveys means that there will usually be at least 4 CCD images,
Table 1. Properties of the repository contents by filter for the better-quality image sets graded A to C.

| Filter | ING/WFC name | N | Exposure (s) | PSF FWHM (arcsec) | Sky count (mag.) | ZP (mag.) | 5σ depth (mag.) | Moon phase |
|--------|--------------|---|--------------|-------------------|------------------|-----------|-----------------|------------|
| i      | WFC SloanI   | 83652 | 10 (83%), and 20 (17%) | 1.06             | 92               | 26.42     | 20.28           | 0.68       |
| Hr     | WFC H6568    | 83652 | 120          | 1.20              | 57               | 26.57     | 20.40           | ”          |
| r<sub>i</sub> | WFC SloanR  | 83652 | 30 (85%), and 10 (15%) | 1.16             | 164              | 28.19     | 21.37           | ”          |
| r<sub>U</sub> | ”           | 67896 | 30           | 1.18              | 126              | 28.20     | 21.67           | 0.21       |
| g      | WFC SloanG   | 67895 | 30           | 1.26              | 61               | 28.71     | 22.38           | ”          |
| U<sub>RG0</sub> | WFCRG0U    | 67892 | 120          | 1.48              | 43               | 27.85     | 21.47           | ”          |

Notes. The number N specifies the number of CCD images available in the A to C grade range for each filter (D-grade images with identified problems are not included in the count). Median values are listed for the full width half maximum of the point spread function (PSF FWHM), the sky background count, zero point (ZP), 5σ detection limit in the Vega system, and moon phase. The PSF FWHM and the background count are pipeline measures, while the ZP and limiting magnitude are based on the uniform calibration (Monguíó et al. 2020). Moon phase is given as a fraction, such that 0 corresponds to new moon and 1 to full moon. The PHOTZP header key-

The H<sub>r</sub> filter magnitude scale is not one conventionally defined within the Vega system. This means we need to define the flux corresponding to the zero of the magnitude scale appropriate to it. We determine that the zero-magnitude flux entering the top of the Earth’s atmosphere within the WFC H<sub>r</sub> filter transmission profile is

\[
F[m(H_r) = 0] = 1.57 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1}.
\] (2)

In the AB magnitude system this is equivalent to a magnitude of 0.328.

Expressed in point-source magnitudes the bright limit of the images is in the region of 11–12 in \( r \) and \( H_r \), rising to 12–13 in the more sensitive \( r \) and \( g \) bands. There were specific observation periods in which WFC electronic issues meant that saturation was reached at appreciably lower count levels than the norm. For example, there was a particular problem affecting CCD 2 in November 2006 that would push the bright limit fainter by up to a magnitude. Users of the data can track such problems in the images via the count level recorded against the header keyword SATURATION.

As part of creating the point-source catalogue images were graded from best to worst as A++, A+, and A to D. A definition of the grades is available in Appendix A of Monguíó et al. (2020). A last point to make about the images is to note that while there is minimal vignetting of CCDs 1, 2, and 4, there is persistent vignetting of the corner of CCD 3 farthest from the optical axis of the WFC (which passes through CCD 4). In Appendix A.2 a typical confidence map is shown to illustrate this. In Appendix A.3 we briefly outline common artefacts in the image data.

3. Accessing the images

All the reduced images from both surveys can be accessed via the website hosted by University College London. Altogether the repository contains 527736 CCD frames, of which 314923 (or 60%) carry the best-quality A grades and 73097 (14%) are minimum-quality D graded. These grade assignments were made at the level of the basic unit of observation in the two constituent surveys – the consecutive trio of exposures obtained at each sky position. The details of the grading system at work in evaluating data for the IGAPS catalogue can be found in...
Appendix A of the catalogue paper (Monguíó et al. 2020). A consequence of this approach, also applied to the earlier IPHAS DR2 release (Barentsen et al. 2014), is that the grade assignment, referred to individual CCD frames or even filters, can be pessimistic, as it takes just one substandard exposure in a set of three to pull down the grade for all of them. In view of this, and the occasional scientific value of maximising the number of images to examine, the decision was taken to retain all D graded data in the repository, alongside the A to C graded exposures.

The images access page within the website offers a search tool that enables users to search for and download images that either overlap a single specified position or occupy a square box of size up to $1 \times 1$ sq. deg. on the sky. The user can choose the filters of interest and decide whether to omit grade D data. In response to a query, the tool returns a table listing the images meeting requirement, along with key metadata (grade, seeing, depth, whether calibrated) that can inform the user’s final choice of images for download. For convenience, there is a column of tick boxes. In the table they allow the user to select some or all of the listed images before initiating the download of a gzipped or tarred collection of Rice-compressed (.fz) images.

The website also provides a link to a large table of metadata that previews the header information provided with the full set of image profiles.

4. Properties of the H$\alpha$ images: Backgrounds and sensitivity

At the outset, the IPHAS survey was allocated time on the expectation that the programme could cope with a moonlit sky. After the first few seasons and some experience had accumulated, the brightest nights were increasingly avoided. Indeed, in the late stages when the acquisition of the blue UVEX filters took priority, dark and grey nights became the norm. The net result is that the median background level among all the uniformly calibrated H$\alpha$ images is closer to grey, than bright. Table 2 provides some numerical detail illustrating the strongly skewed distribution.

| Quantity                        | Percentiles
|---------------------------------|----------|
|                                 | 5       | 50      | 95      |
| Counts                          | 27      | 52      | 210     |
| Vega magnitude (mag arcsec$^{-2}$)| 20.6    | 19.9    | 18.3    |
| Surface brightness (10$^{-15}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$)| 0.91    | 1.7     | 7.4     |

Notes. These are pipeline-computed values obtained for uniformly calibrated images. The sample used here numbers 63956 CCD frames (or 15989 WFC exposures). Not included are the 36808 CCD frames (9202 WFC exposures) for which only the pipeline photometric calibration is available.

In presenting the SHS, Parker et al. (2005) compared its sensitivity with IPHAS and other available H$\alpha$ wide-area surveys. In their Table 1 it was estimated that the depth reached by the narrow-band (IPHAS) data presented here is $\sim 3$ rayleighs. This is a surface brightness of $1.7 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ or, as required by the mean calibration illustrated in Fig. 2, the

$$\frac{N_{bg} = (N_{RN} + \sqrt{C_{bg}})}{\sqrt{n_{pc}}}.$$  

(3)

where $N_{bg}$ and $C_{bg}$ are respectively the sky noise and sky level, $N_{RN}$ is the CCD read noise, also in counts per pixel, and $n_{pc}$ represents the effective number of pixels over which the sky statistics are measured. Basically, we expect the noise to be the sum of a constant and a Poisson component. In practice, the sky level is determined numerically by the pipeline using two-dimensional non-linear background tracking across the full CCD at a super-pixel level. After the background fit has been subtracted from an image, the sky noise is calculated iteratively from the clipped median absolute deviation (MAD) of the residuals.

As the read noise for the WFC is known to be $N_{RN} = 2.37$ counts, we only need to fit one parameter of this function. Before the fitting, outliers above the dashed line in Fig. 3 were removed. The fit was performed using an iterative 3-$\sigma$ clipped Levenberg-Marquardt algorithm using the median and MAD in place of mean and $\sigma$. The result of the fit is

$$N_{bg} = (2.37 + \sqrt{C_{bg}}) / \sqrt{2.88} = 1.4 + 0.589 \sqrt{C_{bg}}.$$  

(4)

Allowing an additional fit parameter, namely a multiplicative factor for the $\sqrt{C_{bg}}$ term, does not lead to a statistically significant improvement in the fit, and the factor is found to be very close to 1. Hence we are confident that Eq. (3) accurately describes the distribution.

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(4) At H$\alpha$, 1 rayleigh is equivalent to $5.67 \times 10^{-18}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$.
Fig. 1. Map of the uniformly calibrated IGAPS field centres (grey). A darker grey colour is seen where the database contains more than one uniformly calibrated exposure. The orange overplotted points mark the 339 exposure sets (1356 CCD frames) without alternatives in the database, where the Hα sky background exceeds 210 counts (>95th percentile).

Fig. 2. Density plot of background surface brightness in the Hα band as a function of measured mean sky level in counts. The colour scale is logarithmic, with blue representing the highest density of points. The images used to build this diagram are the IGAPS uniformly calibrated set, which enables validated conversion of the sky counts to surface brightness via each image’s zero point. The black dashed line has a gradient of $3.32 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ per count. The equivalent of around a half count per pixel in a 120 s exposure at the typical 1 to 1.5 arcsec seeing. The on-sky solid angle that the Parker et al. (2005) estimate refers to was not made explicit – clearly it cannot be 1 arcsec$^2$. If we assume $C_{bg} = 0.5$ counts pixel$^{-1}$ at 3σ, $N_{bg} = 0.5/3$, we can use Eq. (3) to calculate the pixel area needed to achieve a sensitivity of 3 rayleighs. We obtain $18.5 \times 18.5$ pixels or $6.1 \times 6.1$ arcsec.

Fig. 3. Density plot of the pipeline-measured sky noise in the Hα filter as a function of sky level. Both are in units of counts per pixel. The coloured data shown, and plotted on a logarithmic density scale, are drawn from the IGAPS uniformly calibrated set. The solid black line is the fit discussed in the text, given as Eq. (4), that shows that the sky noise increases mainly as the square root of the sky level. The lighter grey data (underneath) are from images with zero points that were not passed through uniform photometric calibration.

Below we present brief discussions of how nebulae can be found and studied, taking the contrasting examples of new PNe and – from the more obscured first phase of the stellar life cycle – a Herbig-Haro object (HHO).

5. Exploitation of the Hα images

The search for and characterisation of extended nebulae was an original goal of the IPHAS component of the merged IGAPS survey. Initially this mostly concentrated on planetary nebulae (PNe). Discoveries of examples of those alternative products of end-state stellar evolution – supernova remnants (SNRs) – have also been found and recorded (Sabin et al. 2013).

5.1. Planetary nebulae

Planetary nebulae are the end-products of low and intermediate mass stars ($\sim 1$–$8 M_\odot$) where a hot central star fully ionises its surrounding shell leading to a glowing nebula. These objects are ideal tools to study the later stages of stellar evolution as most stars in our Galaxy will go through this phase. We can access information related to their physical characteristics via plasma diagnostics (density, temperature, velocity, and so on) and the chemical composition allows the measurement of their impact on the chemical enrichment of any given galaxy. However, most of the known PNe are bright and/or nearby as the faint ones have been ignored or are out of reach due to observational constraints. An aim of IPHAS was to perform a near complete
census of the PNe in the northern Galactic plane, where a higher concentration of ionised sources co-exists with high extinction. Progress towards this goal has been described by Sabin (2008) and Sabin et al. (2014).

5.1.1. Detection methods

Depending on the size of the sources two methods were adopted. On the one hand, compact or point-source PNe have been selected based on Hα excess as measured and recorded in photometric catalogues, and cross-checked against IR photometry (e.g. 2MASS; see Viironen et al. 2009). On the other hand, for the case of extended PNe, a mosaicking process was developed using 2° × 2° Hα − r mosaics with 5 × 5 pixels and 15 × 15 pixels binning factors (corresponding to ~1.7 and ~5 arcsec effective pixel sizes, respectively; see Sabin 2008). The coarser binning was mainly used to detect large and low-surface-brightness nebulae, while the lower binning was aimed at detecting smaller nebulae hidden in crowded stellar fields. In the latter case we also used the technique adopted in the southern MASH survey (Parker et al. 2006; Miszalski et al. 2008) where composite imagery (Hα, r′, and i′ filters) is used to distinguish stars from diffuse ionised nebulae5. Always, new objects were confirmed by independent eyeballing of the data by several team members. This task was found to be ideal for undergraduate projects and two example discoveries are shown below.

5.1.2. New discoveries

Hundreds of new PN candidates were found as a result of the visual search with the mosaics and a first large spectroscopic follow-up involving no less than nine worldwide telescope and instrument pairings, ranging from 1.5 m (ALBIREO spectrograph at the Observatory of Sierra Nevada, Spain) to 10.4 m (GTC-OSIRIS spectrograph at the Observatorio del Roque de los Muchachos, Spain) was conducted (Sabin et al. 2014). We identified 159 objects as True (113), Likely (26) and Possible (20) PNe and unveiled a large range of shapes (mostly elliptical, bipolar and round PNe) and sizes (up to ~8 arcmin).

Among all the newly detected PNe, some caught our attention first due to their outstanding morphology and then due to their interesting characteristics revealed by subsequent deep analyses. Notable examples include: the knotty bipolar IPHASX J194359.5+170901, now known as the Necklace Nebula (Corradi et al. 2011); the quadrupolar IPHASX J012507.9+635652 (alternately named Príncipes de Asturias by Mampaso et al. 2006); IPHASX J052531.19+281945.1 at large galactocentric distance (Viironen et al. 2011); and finally, the PN discovered around the nova V458 Vul (Wesson et al. 2008).

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The second nebula, PNG 95.3+0.2, shown in Fig. 5, was discovered using the same search method by Fernández-Martín (2007). Subsequent high-resolution (0.6 arcsec seeing) imaging with the NOT telescope on the night of 4 September 2007, through Hr, [OIII] 5007 Å, and [NII] 6583 Å filters further clarified an intricate morphology with a bright, roughly elliptical central shell, and a pair of fainter twisted protrusions that show up especially well in the [NII]-only image. Since the IPHAS Hr filter bandwidth also incorporates this line, Fig. 5 is a composite image, showing both the [NII]-dominated outer filamentary structure and the Hr dominated inner ellipse.

PNG 95.3+0.2 is now listed in the HASH Catalogue of Parker et al. (2016). It is associated with an infrared (WISE, and 90 µm AKARI), and 1420 MHz radio source (Taylor et al. 2017). According to Anders et al. (2019), the G = 17.1 mag star near the geometrical centre, IPHAS J213508.15+521128.0, or Gaia EDR3 2171830374492778880, is a distant, reddened, and apparently relatively cold star (\(D = 5.5 \pm 0.9\) kpc, \(A_V = 3.9 \pm 0.2\) mag, \(T_{\text{eff}} = 4800 \pm 260\) K). However, our evaluation of the IGAPS broadband photometry (Monguíó et al. 2020) is that the available magnitudes are also consistent with this object being a much hotter, even more extinguished star. The other two, brighter stars embedded in the nebula are located in the foreground at much more secure parallax-based distances of 0.9 and 1.6 kpc. In the Anders et al. (2019) database they too are assigned low \(T_{\text{eff}}\) values, incompatible with those of a hot PN central star. Vioque et al. (2020) combine IPHAS, 2MASS, and WISE data in a search for new Herbig Ae/Be stars and list IPHAS J213508.15+521128.0 as a non-Herbig AeBe, non-pre-main-sequence, and non-classical Be star – they also do not confirm an association with a PN (their PN flag is empty). The WISE source, detected in the four bands and centred at 1.1 arcsec from IPHAS J213508.15+521128.0, shows red IR colours like known PNe, while the spectral energy distribution of the star, built from Pan-STARRS, 2MASS, ALLWISE, and AKARI data, is typical of a reddened star up to the WISE W3 (12 µm) band. Beyond that, a strong IR excess appears up to 90 µm, and points to a physical association of IPHAS J213508.15+521128.0 with the nebula. If that is the case, the apparent nebular size of around 30 arcsec would imply a rather large, evolved nebula, 0.8 pc in diameter, and also suggest the existence of a hidden hot star (possibly a binary) in the surroundings. PNG 95.3+0.2 is an appealing example of an IPHAS extended object with plenty of online, publicly available information; it nevertheless deserves further dedicated observations, including careful quantitative spectroscopy to pin down the central star.

Basic confirmation spectra exist for both the above nebulae. The objects have also been independently discovered more recently by amateur astronomers. The first object, IPHASX J015624.9+652830, has also come to be known as Ferrero 6, Fe6, and PNG J129.6+03.4, while the second, PNG 95.3+0.2, is also known as SiDr Objet 1. Full details on both can be found in the HASH database (Parker et al. 2016).

5.1.3. Previously known PNe

The survey is also useful for the re-analysis of already known PNe. IPHAS images can unveil new faint structures associated with known PNe that have hitherto evaded detection. A clear example of this is the detection of the extended tail of the known Sh 2–188 by Wareing et al. (2006), which enabled the reevaluation of its full extent. A different application has recently been presented by Dharmawardena et al. (2021): with a view to appraising different methods of determining PN distances, they have collected IPHAS Hr + [NII] aperture photometry fluxes for 151 previously known nebulae as well as for 46 confirmed or possible PNe that had been discovered by the IPHAS survey.

5.2. Herbig-Haro objects

During their growth, young stellar objects (YSOs) eject a fraction of the in-falling matter at high speed via bipolar jets and outflows. Their shock fronts, delineated by line emission, particularly in Hα, [SII], and [OI], are called Herbig-Haro objects (HHOs; Herbig 1950; Haro 1952). These objects not only trace the presence of young stars but can also serve as a record of the accretion history. The kinematics of HHOs, derived from proper motions (PMs) and radial velocities (RVs), allow a kinematic dating of the ejection event. Moreover, such data provide information on the inclination of the circumstellar accretion disc. Constraining the latter is crucial for the analysis of YSO spectral energy distributions using radiative transfer modelling.

The potential of IGAPS for such studies is illustrated by the example of a hitherto unknown HHO, driven by IRAS 01166+6635. This low-mass YSO (Connelly et al. 2008) is emerging from the small dark cloud, Dobashi 3782, situated at a kinematic distance of 240 pc (Wouterloot & Brand 1989). Narrow-band imaging performed in 2007 with the Tautenburg Schmidt telescope revealed a compact HHO south of the YSO within ~1 arcsec of the position RA 01:20:02.9, Dec +66:51:00 (J2000) (Fig. 6). The estimated extinction out to the distance of this cloud is about \(A_V \sim 2.5\), averaged across a few arcminutes (Sale et al. 2014). The extinction towards the optically faint YSO is without doubt much more. At the position of this YSO there are eight entries in the IGAPS catalogue (Monguíó et al. 2020) within a radius of 5 arcsec. Six of the eight are Hα only sources.

Blinking with the POSS1 red image showed evidence for PM within ~50 years. Thus, in order to establish its kinematics, Hα and R-band frames have been secured for as many epochs as possible. Four Hα frames with grade A quality (r367494 and...
The background of astronomical images would ideally be flat and dark. In reality the background in images from ground-based telescopes varies due to the interplay of different sources (e.g. airglow, moonlight) contributing varying levels of unwanted light.

To begin to tackle this securely, when working with the standard image data reduction available in the database, we recommend using the available confidence maps to reject pixels with confidence levels of less than 90–95% typically. But we note that the level can vary across the sky and between filters, usually requiring a lower confidence level threshold for the $g$ filter and especially $U_{RGO}$.

The MONTAGE software\(^6\) can be used to effectively mosaic images in a given filter, re-projecting images as needed to a single-projection algorithm and direction, adjusting the background levels in overlapping pairs of images to produce a smooth mosaic over a large area.

In addition to uniform background light sources, the $i$-band can sometimes be beset by fringing that originates from the airglow OH lines interfering via internal reflections in the CCD chips. This wave-like structure contributes $\sim2\%$ of the total counts in some images (Irwin & Lewis 2001). It is almost entirely removed in the CASU pipeline (who use a library of $i$-band fringe frames from other INT WFC observing runs), although some will remain at the $\sim0.2\%$ level due to night-to-night variations. When $i$-band data are mosaicked, overlapping fringing is occasionally exaggerated and can remain visible in some mosaics.

As noted in Sect. 4, IPHAS observations were at first carried out at any level of moon brightness throughout the Galactic plane season. Observations during bright time were soon found to exhibit varying levels of background counts in the form of a small but noticeable gradient across each CCD (leading in later seasons to tighter moon phase and distance requirements). Ultimately, $\sim8\%$ of all IPHAS images were taken under such conditions.

Moonlight affected IPHAS images through both scattered light across the night sky and a component reflecting off the inside of the telescope dome and across the CCD array. The resulting illumination is therefore not necessarily uniform across all four CCDs, and requires a CCD-by-CCD solution. Its character is also influenced by the phase of the moon, its altitude above the horizon, angular separation from the pointing of the telescope, and the extent (and position) of cloud cover across the sky. These relatively small gradients can be exacerbated by mosaicking CCD images over large areas of the sky (many degrees), becoming a significant issue in the production of large mosaics.

The recommended solution to removing the moonlight and achieving a flat and dark background is to model and fit the background gradient for each CCD. Since the $r$ and H$\alpha$ band images contain nebulosity that could affect the fit, we recommend fitting the background gradient to $r - H\alpha$ images (after scaling the images to correct for their different exposure times), since both filters contain the H$\alpha$ and forbidden [NII] lines that typically dominate diffuse astronomical emission. Binning the image into $100 \times 100$ pixel bins and taking the median pixel value in each bin provides a simple method to measure the background level in that bin. A two-dimensional gradient of the form $Z = Ax + By + C$ can then be fit to the data, where $A$, $B$ and $C$ are free parameters, using, for example a Markov chain Monte Carlo simulation and the Python code emcee (Foreman-Mackey et al. 2013). More complex models have been tested (including Fourier transform techniques), but none were found to provide a significant improvement. In short, the two-dimensional gradient method will prove effective in the majority of cases.

Some care should also be applied when very bright stars fall on (or near) one of the CCDs, as saturation, atmospheric and lens effects can heavily affect an image and the model fit to it. Identifying and excluding a magnitude-dependent radius around

\(^6\) Available from \url{http://montage.ipac.caltech.edu/}

6. Image mosaics

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such stars using the Tycho-2 catalogue of bright stars (Høg et al. 2000) proved effective for overcoming these problems.

As an example of the potential of IGAPS image mosaicking, we present a large, 4.2×3.6 degree Hα mosaic of the SNR Simeis 147, produced using the techniques described above. Simeis 147 (hereafter S147) is otherwise known as SNR G180.0–01.7, Shajn 147, or Sharpless 2–240. It is a large, faint, late-stage remnant located just below the Galactic anticentre. It was discovered in 1952 and lies at a distance of 0.8–1.6 kpc (Gvaramadze 2006), on the near side of the Perseus spiral arm. The SNR consists of numerous filaments embedded in large-scale diffuse emission. The eastern and western edges of S147 show signs of blowouts, the southern edge shows a sharp boundary, with a less regular one in the north. The undistorted appearance of the SNR may partly be due to it expanding into a region of space already partly cleared by a previous supernova (Gvaramadze 2006). Regardless, examples of large and pristine SNRs are rare and observations of them can be important for constraining hydrodynamic simulations of their expansion and structure.

Figure 8 shows the full mosaic constructed as outlined above. The challenge of this object is its great size, allied with very intricate and sometimes very faint small-scale detail. The number of individual CCD frames included is in the region of 250. The full-resolution S147 mosaic (199 MB) itself is provided as a fits-formatted file which can be downloaded from the IGAPS website.

7. Nebular target selection for massive-multiplex spectroscopy

The next decade will see an increase in large, multi-object digital spectroscopic surveys on 4 m class telescopes. In drawing up target lists, these surveys will make use of the data that has been acquired by wide-area digital photometric surveys, like IGAPS. Two examples due to start soon are the WEA VE survey on the 4-m William Herschel Telescope (WHT) of the Roque de los Muchachos Observatory in La Palma (Dalton et al. 2020) and the 4MOST survey on the 4-m VISTA telescope operated by ESO at Paranal (de Jong et al. 2019). Both facilities will collect of the order of 1000 targets per pointing, and a major science driver for both is Milky Way science in the Gaia era.

Massive-multiplex spectroscopy requires informed target selection. The IPHAS Hα images, in particular, can characterise the diffuse sky for studies of the ionised ISM. Here, we outline...
7.1. Building lists of science targets with HAGRID

A WEA VE pointing is defined by the coordinates of its centre and a field of view of radius of 1 degree, projecting a circle on the sky covering \( \pi \) sq. deg. Within such a field, the aim is to identify several hundred positions that coincide with regions of (locally) maximum H\( \alpha \) brightness.

In outline, the steps taken are as follows: (i) find all H\( \alpha \) CCD images from the IGAPS repository in the area of interest; (ii) mask out stars, CCD borders, bad pixels, and vignetted areas from the data; (iii) divide the image into superpixels; and (iv) select the superpixels with the highest counts as candidate source positions.

The application of the algorithm, confronted with real data, is necessarily more complicated, particularly as it must deal as far as possible with all the artefacts that mimic real nebulosity. So we now itemise the steps involved in more detail.

The first step is to collect the CCD images from the IGAPS repository in the area of interest. For one WEA VE field of radius 1 degree, this will be a list of over 100 H\( \alpha \) CCD frames and their associated \( r_f \) exposures. Since frames with poor data quality often lead to false detections of H\( \alpha \) emission, we excluded, where possible, grade C and D frames and favoured uniformly calibrated data.

The second is to create a star mask for each CCD image from both the IGAPS point-source database and a bright star catalogue to identify stars needing larger exclusion zones. The mask radius of IGAPS sources is set as a function of \( r_f \) magnitude, H\( \alpha \) seeing and ellipticity. Also masked are diffraction spikes of bright stars and a visible halo for very bright stars (\(<4.5\) mag; see the right panel of Fig. 9). The halo position relative to the star depends on the angular separation of the star from the optical axis of the telescope.

Third, other artefacts are also masked. These include CCD borders, pixels that fall below a specified threshold in the linked confidence map (see Appendix A.2), hot or cold pixels, and artificial linear structures (satellite trails, noise bands, gain-change strips, bright star reflections, etc.) found by visual inspection.

The fourth step is to create superpixels and rank them by H\( \alpha \) brightness. Each masked CCD frame is divided into superpixels, which are squares of \( n \times n \) native pixels, where \( n \) is an adjustable input parameter. For WEA VE, \( n = 25 \) giving \( 8.25 \times 8.25 \) arcsec\(^2\) superpixels. This choice tensions between good-enough angular resolution and the typical loss of area and statistics inflicted by the masking. Superpixels that are more than 50% masked are rejected. To avoid particle hits being mistaken for astronomical signal, the data are median filtered using \( 3 \times 3 \) pixel (about 1 arcsec\(^2\)) binning. The superpixels are then ranked by mean count determined from the unmasked pixels.

The fifth is to estimate the H\( \alpha \) sky background. A sound determination of the local sky value is very important, especially for determining the correct H\( \alpha \) surface brightness. The algorithm measures the sum of sky and any significant astronomical background from the H\( \alpha \) frames. In predefined areas of extensive and intense nebulosity we also derive an estimate of the H\( \alpha \) sky-only background value from the \( r_f \) sky value. This uses a linear fit to a global plot of the H\( \alpha \) against the \( r_f \) sky level, exploiting the fact that most of the Galactic plane is free from nebular emission. If the sky value inferred from \( r_f \) is lower than the H\( \alpha \) sky value, then we adopt the average of the two. Taking the average was precautionary against problems with the \( r_f \) sky prediction due to changing moonlight reflections into the telescope from clouds and other structures such as the dome.

The sixth is to select H\( \alpha \)-excess source positions from the ranked superpixel list for every CCD frame. The superpixel list is searched starting at the highest mean count. A superpixel is rejected if: it is closer than a distance limit (1 arcmin for WEA VE) to an already selected superpixel; the difference between the superpixel mean and the frame H\( \alpha \) sky is less than the sky noise (one sigma). Finally, the maximum \( 3 \times 3 \) pixel mean-filtered count within the superpixel is located and its position is adopted as the candidate target position. If the difference between this more localised mean and the H\( \alpha \) sky is \( >10 \) ADU, the superpixel goes forward into a merged overview table.

Seventh, the location, count, surface brightness, and other data for each selected high-H\( \alpha \) candidate position is appended to the overview table, which covers a large user-defined sky area that is ready for further checking and analysis.

As it searches for positions of bright H\( \alpha \) emission, HAGRID also identifies suitable low-count sky positions and gathers statistics on sky noise. The distribution of sky noise versus sky background it finds closely resembles the distribution found by the pipeline shown in Fig. 3. The sky noise measured by HAGRID is lower as it does not involve a fit over the whole CCD and so avoids contributions from fainter stars.

The algorithm can be applied to areas of arbitrary size. As each CCD is independent of the others, the code parallels very...
effectively. The choices of minimum distance between accepted source positions is driven mainly by the design of the destination wide-field spectrograph, and the anticipated observing strategy. For WEAVER, applying the 1 arcmin minimum distance between fibre placements led to at most ~200 source positions selected per WFC CCD (with a much lower median of 5).

7.2. Final processing: List cleaning and reduction

The list of potential target positions generated for WEAVER as described above was long and needed further cleaning and reduction. Not everything that appears bright in Hα and is passed through by HAGRID has an astronomical origin: for example, some satellite trails, ghosts and unrecognised haloes around brighter stars can remain (Fig. 9). There are a number of further test-and-eliminate steps that can be taken to reduce the list to a high-confidence core. One such step is to favour repeat selection of the same emission structure and to reject isolated points by cuts applied in the Nt trend lines. These distances, to the expected nebular and stellar fields, are then expressed as a density map and before any second-stage cleaning. The selection shown is from the sky region: (30° ≤ l < 95°, |b| < 4°). Working from top to bottom the red lines are: equality between counts (shown dashed), a line of slope 0.77 (solid) representative of nebula-dominated positions, and a line of slope 1/13 (solid) characteristic of star-like positions.

Fig. 10. Excess Hα-band counts compared with the excess counts in the r band. Both quantities are the difference between the measured peak count and the estimated background level returned by HAGRID. It should be noted that the HAGRID output list is restricted to excess narrow-band counts >10. The data are plotted as a density map and before any second-stage cleaning. The selection shown is from the sky region: (30° ≤ l < 95°, |b| < 4°). Working from top to bottom the red lines are: equality between counts (shown dashed), a line of slope 0.77 (solid) representative of nebula-dominated positions, and a line of slope 1/13 (solid) characteristic of star-like positions.

because of other nebular lines within the r band, not captured by the narrow band (e.g. the [SII] 671.6, 673.1 nm doublet that can be strengthened by shock excitation, and potentially some [OI] 630.0, 636.2 nm emission). The approximate regression line shown in Fig. 10 has a slope less than 1, for this reason. The objects of the search are indeed the candidate positions clustered around this empirical trend and, as such, they are the ones to keep.

In contrast, the second much lower gradient trend apparent in Fig. 10, running close to the horizontal axis, is created by sky locations where the spectrum is continuum-dominated (i.e. star-like). These locations can be stellar haloes where HAGRID picks up a seeming Hα excess thanks to the typically wider seeing profile in the longer and unguided narrow-band exposures, or ghosts (see Fig. 9 for examples). In the case of a typical 0.5 ≤ r − i ≤ 1 stellar continuum across the r band, the expectation would be that the narrow-band excess counts would be approximately 1/13 of the r counts − this is the last of the three lines superimposed in Fig. 10. Candidate positions of this type need to be removed.

To make an accept/reject decision for every candidate position in the list, the distances to the expected nebular and stellar trend lines are calculated. These distances, Nt, are then expressed scaled to σ, the relevant Poisson-like error on the computed distance (subscript n for nebular, s for star-like). This is followed by cuts applied in the Nt, Ns plane to select the most credible nebular targets. Inevitably, at low count levels, the confidence in assigning a candidate to the ‘nebular’ and ‘star-like’ classes weakens greatly. The minimum excess count of 10 imposed by HAGRID helps deal with this, but a minimum cut on Ns is also needed. Where it is placed has to be tested empirically: for WEAVER we required Ns > 3.5.

The selection can also be trimmed down to surface densities appropriate to the instrument used and the survey observing strategy (e.g. number of visits, required science sampling). In the case of WEAVER this meant a 2 arcmin grid was placed over the relevant sky area and only two positions with the highest flux were kept in each grid cell. Taking all the steps together for the WEAVER example, the original list of about 1.3 million target positions reduced to under 200 000 potential targets, of which we expect around one-fourth to be selected for observing.
Fig. 12. Comparison between HAGRID generated flux levels and the calibrated map of Finkbeiner (2003). Top: map of HAGRID-selected positions in the Cygnus-X region of the northern Galactic plane. Every selected position has been coloured according to the logarithm of the estimated surface brightness (in ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$). White areas will have log(surface brightness)$ < -15.5$. The region shown spans 50 sq. deg., or 3.6% of the total area processed, and contains 20% of the identified candidate target positions. It is the most line emission-rich part of the northern plane. Bottom: same area in the Finkbeiner (2003) H$\alpha$ map, with 6 arcmin pixels. The data available in this region are a combination of images from VTSS (circular footprint) and WHAM (making up the much coarser resolution background).

7.3. Testing the downsize against known Herbig-Haro objects

We performed a retrospective test that compared the character of the long list with that of the final downsize by cross-matching them both with a list of known HHOs. This list was established by a CDS criteria query using the term otype='HH'&ra>0. The coordinate condition was necessary to dismiss about 800 entries without coordinate information. The resulting table comprised 2622 positions; just 388 of them lie in the sky region defined by the Galactic coordinate ranges, $30^\circ < \ell < 210^\circ$, $|b| < 4^\circ$ (roughly the footprint HAGRID has been applied to). When a limit of 10 arcsec was set on the angular separation, there were 70 and 40 successful cross-matches with the HAGRID long and short lists, respectively. These numbers dropped to 45 and 27 when the limit on angular separation was reduced to 5 arcsec.

That no more than 20%, at best, of the listed HHO in the region were recovered is attributable to HHO position uncertainties, their high PM and the relatively low surface brightness of many. Another occasional factor at work will be the presence of substantial scattered starlight lowering the contrast between the H$\alpha$ and $r$ images to below an acceptance threshold (emission in the vicinity of V645 Cyg is subject to this). The most relevant point is that the down-sized list of candidate emission line positions captured more than half the number matching with the long list, despite the fact it contained only $\sim 0.15$ as many positions. Proportionately, the shorter list was appreciably better, indicating that the downsizing had the side benefit of raising list quality.

7.4. Results of selection

The distribution of diffuse ionised emission in the northern plane is heavily weighted to low surface brightness and its presence
along the plane is extremely uneven. These are the outstanding features of the out turn from the application of HAGRID to the IGAPS image database. The extent to which low surface brightness is favoured is illustrated by the histogram of excess \( \alpha \) counts, presented as Fig. 11. The mean of the distribution is 32.5 excess counts, while the more informative median is just 21.6 (translating to a surface brightness of \( \sim 7.2 \times 10^{-16} \) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\) or close on 130 rayleighs).

The upper panel of Fig. 12 is a cut-out of 50 sq. deg. in the Cygnus-X region of the plane, a region that is very rich in ionised gas: around 20% of all the selections are contained in just this 3.6% of the processed sky area. Every data point is a candidate target position and is coloured according to the logarithm of \( \alpha \) narrow-band surface brightness. The figure amounts to a ‘pointilliste’ rendition of an \( \alpha \) image of the region emphasising the brightest locations. Comparison with the much coarser angular resolution \( \alpha \) map presented by Finkbeiner (2003), in the lower panel of Fig. 12, shows that the larger-scale structure in the \( \alpha \) surface brightness is shared, with the important difference that the HAGRID output offers much better resolved, brighter detail that vanishes when smoothed to several arcminutes.

The bright North America Nebula is located towards bottom left in both panels. The hole in the emission in the top right corner of the upper panel is a product of needing to leave a zone clear around the 2nd magnitude star, \( \gamma \) Cyg. The larger hole below it is real in the sense that it is a dark cloud free of line emission.

A further example of the candidate positions output by HAGRID and the subsequent reduction is presented in Fig. 13 for the case of S147 (already discussed and illustrated in Sect. 6). Its appearance is very filamentary, somewhat resembling a collection of soap bubbles, with the filaments at the interfaces. The overall distribution of emission is captured very well by the selection, as shown by the comparison with the excerpt from the Virginia Tech Spectral-line Survey (VTSS, Dennison et al. 1998), in the upper panel of Fig. 13. However, the 1.6 arcmin pixel scale of VTSS does not entirely resolve the structure present. The filaments, with typical widths of under 1 arcmin, emerge more clearly in the IGAPS narrow-band imagery, thanks to its native \( \sim 1 \) arcsec angular resolution. This is picked up faithfully by the HAGRID selection. The surface brightness of the selections ranges from \( 3 \times 10^{-16} \) to (very infrequently) \( 3 \times 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\)

8. Closing remarks

A goal of this paper has been to present and describe the new IGAPS image database, formed from merging the data from the IPHAS (Drew et al. 2005) and UVEX (Groot et al. 2009) surveys of the northern Galactic plane. Around two-thirds of the database carries photometric zero points from the uniform calibration described previously by Monguió et al. (2020). The collection is complete in that it contains all images of all qualities obtained over the course of the two long-running survey programmes. This creates options for comparing different epochs given that many fields were observed more than once.

The main focus of this paper has been on the \( \alpha \) narrow band: the only one of the IGAPS set expressly targeting line emission. Before summarising what we have presented on \( \alpha \), we recall that the Sloan \( g \) band contains within its range the sometimes extremely bright [O III] 495.9, 500.7 nm doublet. Accordingly, images taken using this filter can be used to compare and contrast the appearance of prominent nebulous regions in low ionisation lines (\( \alpha \) and the [N II] 654.8, 658.4 nm doublet) and the much higher ionisation [O III]. This will work especially well for lower extinction sightlines, where the [O III] lines are not disadvantaged by dust obscuration on top of the 1:4 exposure time ratio. An outstanding example of such a comparison, for the Dumbbell Nebula, is shown as Fig. 14. This is a large and bright PN in which it can be seen that the [O III] emission (\( g \)-band image, upper panel) is less clumpy than the \( \alpha + [\text{N II}] \) emission (\( \alpha \) image, lower panel), while the extent of the main nebula is nearly the same in both. Furthermore, even in the \( g \) band 30-s exposure, fainter more extended structure is also apparent beyond the main nebula rim (seen to the west, i.e. to the right in the figure). Its existence was first noticed in the lower-resolution narrow-band images presented by Papamastorakis et al. (1993). The central star also stands out at this shorter wavelength. The price paid for this kind of direct exploitation is, necessarily, the strong pickup of starlight in the field because the \( g \) band is broad. Some improvement on this might be achieved by constructing \( g - r \) difference images.

Returning to our main aim, we have provided a characterisation of the distinctive narrow-band \( \alpha \) data whilst also showcasing some new illustrative applications. Thanks to the Monguió et al. (2020) zero point calibration, it is now more certain what the noise levels and sensitivities are: At full \( \sim 1 \) arcsec angular resolution it is possible to distinguish the nebulousity of...
The full collection of IGAPS images is available to the community online.\footnote{http://www.igapsimages.org} This website provides an interface that facilitates downloads of selected images, served up as individual CCD frames. It also provides a number of related resources, including the HAGRID-generated list of bright diffuse Hα northern-plane positions presented here.

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Fig. 14. Dumbbell Nebula: as imaged in the g and Hα bands (upper and lower panels, respectively). The g image includes the strong [OIII] 495.9, 500.7 nm lines. The cutouts are taken from the same corner of CCD #2 in runs r-477762 and r-1241402, picked for having well-matched seeing (respectively 1.31 and 1.25 arcsec). The colour scales used are capped at 1250 counts for g and 5000 counts for Hα to match the ratio of their exposure times. They run from black at background level up through green/magenta/red to yellow at the bright end. This PN has a diameter of approximately 6 arcmin. North is up, east to the left.

surface brightness down to \(2 \times 10^{-16} \text{ ergs cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}\) (the typical noise level). We have described here, in detail, how this may be exploited on a large scale to build target lists for diffuse-ISM spectroscopy using the coming generation of massive-multiplex wide-field spectrographs (Sect. 7 on the HAGRID algorithm). On re-binning the native 0.333 arcsec pixels, the sensitivity increases as expected: Sabin et al. (2014) already claimed a typical sensitivity of \(10^{-17} \text{ ergs cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}\) for 5 x 5 arcsec\(^2\) binning. We endorse this, with the necessary qualification that, in reality, there will always be a range in sensitivity, linked directly to the prevailing background level (see Fig. 3).

So far, most science exploitation of IGAPS image data has been directed towards PN[e and, to a lesser extent, SNRs. We acknowledge this, with the necessary qualification that, in reality, there will always be a range in sensitivity, linked directly to the prevailing background level (see Fig. 3).
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Appendix A: Image properties and common artefacts

Here we comment briefly on the known $U_{\text{RGO}}$ and $g$ point spread function (PSF) variations and present an example of a confidence map. We then describe artefacts that one might come across in the survey imagery, especially in lower graded images. These are not unique to the WFC, as they can be found on most imaging instruments. We include this additional material to place it on record for the benefit of future users who may be less familiar with these oddities. The survey data acquisition and pipelining has been described in previous papers (Drew et al. 2005; González-Solares et al. 2008; Groot et al. 2009; Barentsen et al. 2014; Monguíó et al. 2020), with relevant aspects summarised here in Sect. 2.

A.1. $U_{\text{RGO}}$ and $g$ PSF variations

The $U_{\text{RGO}}$ filter stands out among the filters used by the IGAPS survey in being a liquid filter: between 1mm UG2 and UBK7 glass plates lies a 5mm thick CuSO$_4$$_2$ solution.

The liquid nature of the filter leads to different image properties of the $U_{\text{RGO}}$ data. Figure A.1 shows a typical pipeline measured ellipticity distribution for the $g$ filter on the left, as an example representing the four normal glass filters used by IGAPS. The pixel distance to the instrument rotator centre, which should be close to the optical axis, is shown on the x-axis. The data for all 4 WFC CCDs is combined in this plot. A running median is plotted as the thick black line. It can be seen that the ellipticity depends on the radial distance from the optical axis. The right panel of Fig. A.1 shows the same information for the liquid $U_{\text{RGO}}$ filter. A single radial trend does not exist. This leads to a more erratic PSF (see the right-hand panel of Fig. A.2). It is also the reason why an additional fifth-order term is sometimes necessary for the astrometric solution (Monguíó et al. 2020). It can also be seen in this example that, despite being a low extinction region, the number of sources visible in the 120 second $U_{\text{RGO}}$ exposure is clearly less than in the 30 second $g$ exposure. The change in point-source image morphology across the WFC array also has an effect on the morphological classification of sources, which are less likely to be classified as stellar the further they are located from the optical axis, independent of the filter (cf. Sect. 2.2 in Farnhill et al. 2016).

As the seal around the edges of the $U_{\text{RGO}}$ filter is not completely tight, the contained solution slowly evaporates over time and hence needs to be topped up whenever an air bubble becomes apparent. Occasionally observations were made with a bubble visible in the filter, which always will drift to the filter edge in zenith direction. At minimum the red leak of the $U_{\text{RGO}}$ filter would be increased for stars observed in the bubble area. Accordingly, bright patches of stars near the edge of frames should be viewed with caution.

During the creation of the IGAPS catalogue it was discovered that there is also an optical blemish on the surface of the $g$ filter, which has an effect on the image quality. The location of this blemish changed over time, depending on the orientation in which the filter was reinserted into the filter holder after cleaning. More information is available in Sect. 6.1 and Appendix B of Monguíó et al. (2020).

A.2. Confidence maps

The confidence maps produced in pipeline processing are used for the masking of bad pixels and vignetted areas on the CCDs. The pipeline produces the confidence maps per filter from the observations of flat fields taken during an observing run. Hence each IGAPS observing run has its own set of confidence maps associated with it. The confidence map is referenced in the FITS header item CONFMAP (see Appendix B). To define bad pixels, often a limit of confidence $<90$ is used. Figure A.3 shows an example of a confidence map. The vignetting of the image area is clearly visible. The use of a round filter in the WFC has its biggest impact on CCD#3, but also affects corners of CCD#2 and CCD#1.

The worst column defects are also visible in the figure. Many thinner column defects and small bad pixel areas are not visible at this image resolution. For specific purposes, such as the selection of diffuse-ISM targets for wide-field spectrographs as described in Sect. 7, the automatic selection of bad pixels via the confidence maps can benefit from the addition of further hot and cold pixels identified by the user.

A.3. Artefacts

A number of artefacts can be found on the IGAPS WFC images, just as they are in data from a range of astronomical cameras. The cause of these are optical reflections, external particle or light sources, or electronic components.

A.3.1. Bright stars

For bright stars even the faintest parts of the PSF become visible. The right panel of Fig. 9 shows a bright star and its associated halo, with a radius of $\sim$1100 pixels. It can be seen that the halo is offset from the star. This offset depends on the distance to the optical axis of the WFC, which hints at the reflection being caused by a curved optical surface. As shown by this example, the halo of a bright star can affect a considerable part of a CCD.

Apart from the direct image and halo, the light of a star also gets reflected onto different optical surfaces of the instrument and forms several large reflections, which can appear more than a degree from the star (‘ghosts’). In the case that a star is very bright, these reflections will become visible in the images. One example is shown in the left panel of Fig. 9. The reflection nearly covers a full CCD, and a lot of fine detail from the telescope entrance pupil can be made out – including the cabling of the WFC at the prime focus that protrudes beyond the central obstruction. Also visible is part of a fainter large reflection in the top right corner of the CCD. The seemingly small bipolar nebula at the bottom of that fainter reflection is not real either. That it is just reflected light can be checked by inspecting the offset partner image of the same sky location.

Reflections do not always have to appear complete or have a circular shape. Figure A.4 shows the superpixel map created by HAGRID, as described in Sect. 7.1, as this makes low level detail more readily visible. The left panel of that figure shows two odd reflections. One with a square appearance, which is actually just a cutout from a much larger circular reflection. The other one visible in the top right corner of the CCD is quite different in appearance from the usual circular reflections. The right panel shows part of a circular reflection from a star outside the CCD. On top of it is a smaller, more elliptical reflection. Also visible in this superpixel map is low level fringing outside of the areas covered by the reflections. And the effect of vignetting on CCD#3 is also clearly discernible.

Figure A.5 shows the effect of a bright star located at or near the edge of a CCD. This leads to the starlight being reflected on to the CCD at an oblique angle. The left panel shows that this
Fig. A.1. Dependence of pipeline measured source ellipticity on the distance to the instrument rotator centre. The data are from IGAPS field 6395o and show the sources from the $g$ image r584231 on the left, and from the $U_{RG0}$ image r584230 on the right. On the left the data of all four CCDs are shown together with a running median plotted as a black line. On the right the data from each CCD are shown with different colours and symbols: CCD#1 as red filled dots, CCD#2 as blue plus signs, CCD#3 as green triangles, and CCD#4 as orange squares.

Fig. A.2. Cutout from CCD#3 of images r584231 ($g$ filter, left) and r584230 ($U_{RG0}$, right), showing the difference in PSF appearance between these filters.

Fig. A.3. Confidence map for the Hα filter from November 2012. Areas shown in black have a confidence value < 50. The layout of the CCDs has #2 on top, and #3, #4, and #1 from the left at the bottom.

Fig. A.4. Reflections of bright stars outside the CCD. Left: Image r430532, CCD#1, Hα filter. The reflection in the centre is up to 25% of the background. The one near the top reaches more than 300% of the background counts. Right: Image r764550, CCD#3, $i$ filter. The large and small reflections have 6% and 21% more counts than the background, respectively. The visible fringing is at about 1.5% of background. The HAGRID superpixel map is shown to enhance low level detail. Black areas correspond to rejected superpixels due to high levels of masking. The colour scale goes from red (low values) to blue (high values).

...creates a cometary tail like structure that can extend quite a distance from the star. Also, an almost-square reflection is visible near the top edge, along with a fainter circular reflection. The mask created by HAGRID (cf. Sect. 7.1) is shown in the right panel. It can be seen that this reflection creates a lot of faint spurious sources, picked up erroneously by the IGAPS catalogue, which are arranged in the circular pattern of the reflection. Further spurious sources can be seen extending along the cometary reflection. A further faint part of a circular reflection must exist at the centre of the right CCD edge, as another circular structure of spurious sources can be seen there.
Fig. A.5. Reflection of a bright star on image r414326, CCD#2. On the left side the H$\alpha$ image is shown. The pixel mask is shown on the right. Black corresponds to masked pixels. The bright star is located just outside the top edge of the CCD. This creates a cometary-like tail that covers about half the CCD length and a square reflection near the CCD top. The usual circular reflection is also visible at the top. As the masked pixels are generated from the catalogued sources, it can be seen that a lot of faint spurious sources are detected due to the reflections.

Fig. A.6. Examples of prominent cosmic ray impacts. Top left: Worm caused by multiply scattered low energy electrons. The other three panels show muon impacts. The images are: top left, r372612 CCD#4; top right, r418359 CCD#2; bottom left, r431220 CCD#2; bottom right, r570439 CCD#3. Each cutout is 180 pixels squared.

A.3.2. Cosmic rays and satellite trails
Cosmic ray impacts are a well-known nuisance in astronomical images (Smith et al. 2002). Despite their name, not all impacting particles actually are of direct cosmic origin. Figure A.6 shows a few prominent examples of particle impacts visible in the 120s H$\alpha$ exposures. The long streaks visible in the right hand panels are caused by muon impacts. The track in the lower left panel shows a kink in the track, probably due to a collision with a particle in the CCD. The top left panel shows a so called ‘worm’, caused by multiply scattered low energy electrons.

Fig. A.7. Details of the satellite track on the H$\alpha$ image r541904, CCD#3. Two excursions away from linear are shown. Telescope tracking or satellite structure might have caused them.

Another nuisance in astronomical images are satellite tracks. With the current and future planned mega satellite constellations in low earth orbit, this problem is very much on the increase. Satellite tracks are mostly straight lines running through the image at an angle. Sometimes flares can be seen, where the brightness increases for a short time due to the alignment of reflecting satellite surfaces with the observing direction. Rather rare is the observation of fine structure in the satellite track. One such example can be seen in Fig. A.7. The cause of these high frequency ‘wiggles’ may either be due to telescope-tracking glitches in declination or to satellite spin bringing different structures into illumination.

A.3.3. Pickup noise and gain changes
Occasionally the WFC images suffer from electronic noise, either from external sources (pickup noise) or from readout electronic problems (gain changes). Over time, with ageing electronics, especially the gain changes became more common. The occurrence of gain changes seems to be random, and subsequent images usually are read out correctly. In most cases there is only one gain change during the readout. As certain observing runs had an increased occurrence rate of gain changes, not all of the affected fields could be re-observed at a later date. Hence the data reduction pipeline was modified to deal with the gain changes and still produce a useful object catalogue. An extreme example of many gain changes during the readout is shown in Fig. A.8 in the right panel. These extreme cases could not be salvaged by the data reduction.

The left panel of Fig. A.8 shows an image with typical pickup noise.

A.3.4. Cross talk
Cross talk during readout is a well-known phenomenon for CCD arrays (Freyhammer et al. 2001). With the WFC, cross talk only becomes visible when a very bright source falls on one of the CCDs. An example is shown in Fig. A.9. The bright star in CCD#1 creates a negative cross talk in CCD#2 at a level of about -10 ADU. CCD#4 shows a positive cross talk at about 10 ADU, and CCD#3 only shows a very small positive cross talk signal in this case.

A.3.5. Multiple images
Very rarely, multiple images of each source are found on an IGAPS exposure. Normally these appear as double images or streaks. The latter effect is caused by the telescope not being settled on the observing position by the time of exposure start. The former is caused by jumps in the telescope tracking or, in the case of the INT, the oscillation of the main mirror support system (see
Fig. A.8. Examples of the impact of pickup noise and gain change on CCD images. Left: Pickup noise on image r1018959, CCD#4. The variations here are small and represent minor degradation. Right: Gain changes on image r1166073, CCD#4. The changes are both spread across the whole and large, rendering this frame unusable.

Fig. A.9. Cross talk on image r1023036: CCD#1 is shown top left, #2 top right, #3 bottom left, and #4 bottom right. The same pixel section is shown for each CCD. The bright star on CCD#1 is seen as a negative imprint on #2 for pixels that are saturated, as a positive imprint on #4, and as a faint positive imprint on #3.

Fig. A.10. Double images on frame r367586, CCD#4. Bright stars clearly show the sign of INT mirror support oscillation, forming dumbbell-like images.

Fig. A.11. Examples of rare image artifacts. Left: Image r418779, CCD#4. The left and right edges show a 5% difference in background counts. Right: Image r531376, CCD#4. The feature, top right, causes up to a 10% difference relative to the background. The HAGRID super-pixel map is shown to enhance low level detail. Black areas correspond to rejected superpixels due to high levels of masking. The colour scale goes from red (low values) to blue (high values).

A.3.6. Other

Very occasionally images suffer rare, sometimes unexplained artefacts. Two such examples are shown in Fig. A.11. The left hand panel shows reduced counts near the left and right edge of the CCD. This effect is visible in CCDs 2 and 4, but not in CCDs 1 and 3.

The right hand panel of Fig. A.11 shows the effect of a drop of liquid (water or oil) on the filter. This happened during the two nights of 10 and 11 October 2006. The extent and form of the feature changed over time during these nights.
Appendix B: CCD image header content

The table below provides an example of the header content associated with each CCD image file. Much of this information is also captured in the metadata table available for download in compressed form as igapsimages.org/data/images/igaps-images.fits.gz.

Table B.1. Image header content.

| Parameter         | Example value | Explanation                                      |
|-------------------|---------------|--------------------------------------------------|
| BITPIX            | 8             | Data type of original image                       |
| NAXIS             | 2             | Dimension of original image                       |
| NAXIS1            | 2048          | Length of original image axis                    |
| NAXIS2            | 4096          | Length of original image axis                    |
| PCOUNT            | 0             | Size of special data area                        |
| GCOUNT            | 1             | One data group (required keyword)                |
| RUN               | 677729        | Run number                                       |
| OBSERVAT          | LAPALMA       | Name of observatory (IRAF style)                 |
| OBJECT            | intphas_5023 r| Title of observation                             |
| LATITUDE          | 28.761907     | Telescope latitude (degrees)                     |
| LONGITUD          | -17.877559    | Telescope longitude (degrees)                    |
| HEIGHT            | 2348          | [m] Height above sea level.                      |
| SLATEL            | LP02.5        | Telescope name known to SLALIB                   |
| TELESCOP          | INT           | 2.5m Isaac Newton Telescope                      |
| MJD-OBS           | 55015.0452356 | Modified Julian Date at start of observation    |
| JD                | 2455015.5452356| Julian Date at start of observation            |
| PLATESCA          | 6.856013      | [d/m] Platescale (24.68arcsec/mm)                |
| TELFOCUS          | 0.043825      | Telescope focus (metres)                         |
| AIRMASS           | 1.021475      | Effective mean airmass                           |
| TEMPTUBE          | 13.508864     | Truss Temperature (degrees Celsius)              |
| INSTRUME          | WFC           | INT wide-field camera is in use.                 |
| WFFPOS            | 5             | Position-number of deployed filter               |
| WWFBAND           | r             | Waveband of filter                               |
| WFFID             | 214           | Unique identifier of filter                      |
| SECPPIX           | 0.333         | Arcseconds per pixel                             |
| DETECTOR          | WFC           | Formal name of camera                            |
| CCDXREAD          | FAST          | Readout speed                                    |
| CCDDYBIN          | 1             | Binning factor in x axis                         |
| CCDDYBIN          | 1             | Binning factor in y axis                         |
| CCDXSUM           | 1 1           | Binning factors (IRAF style)                     |
| CCDELEVENT        | 151.959       | [K] Cryostat temperature                         |
| NWINDOWS          | 0             | Number of readout windows                        |
| DATE-OBS          | 2009-07-03T01:05:10.8| Start time of the exposure [UTC]                  |
| INHERIT           | T             | Extension inherits primary HDU.                  |
| EXTNAME           | extension1    | Extension name                                   |
| EXTER              | 1             | Extension version number                         |
| IMAGEID           | 1             | Image identification                             |
| DASCHAN           | 1             | Number of readout channel                        |
| WINNO             | 0             | Number of readout window                         |
| CHIPNAME          | A5506-4       | Name of detector chip.                           |
| CCDNAME           | A5506-4       | Name of detector chip.                           |
| CCDCHIP           | A5506-4       | Name of detector chip.                           |
| CCDELEVENT        | EEV42-80      | Type of detector chip.                           |
| CCDSUM            | 0.00001350    | [m] Size of pixels in x.                         |
| CCDDYBIN          | 0.00001350    | [m] Size of pixels in y.                         |
| AMPNAME           | LH            | Name of output amplifier.                        |
| GAIN              | 2.800000000  | Nominal Photo-electrons per ADU.                 |
| READNOIS          | 6.400000000  | Nominal Readout noise in electrons.              |
| SATURATE          | 64276.0       | Highest value that is unsaturated                |
| BIASESP          | [11:50,3:4098]| Bias pixels.                                    |
| TRIMSEC           | [51:2098,3:4098]| Illuminated pixels.                              |
### Table B.1. continued.

| Parameter       | Example value          | Explanation                                                                 |
|-----------------|------------------------|-----------------------------------------------------------------------------|
| RTDATSEC        | [2062:4215,13:4212]    | Location in d-space for RTD.                                                |
| RADESYS         | ICRS                   | WCS calibrated against Gaia-DR2                                             |
| EQUINOX         | 2000.0                 | Equinox of the astrometry                                                  |
| CTYP1           | RA ZPN                 | Algorithm type for axis 1                                                  |
| CTYP2           | DECZPN                 | Algorithm type for axis 2                                                  |
| CRUNIT1         | deg                    | Unit of right ascension coordinates                                         |
| CRUNIT2         | deg                    | Unit of declination coordinates                                            |
| PV2_1           | 1.0                    | Coefficient for r term                                                      |
| PV2_2           | 0.0                    | Coefficient for r**2 term                                                   |
| PV2_3           | 213.741679             | Coefficient for r**3 term                                                   |
| PV2_5           | 0.0                    | Coefficient for r**5 term                                                   |
| CRVAL1          | 292.931917 [deg]       | Right ascension at the reference pixel                                     |
| CRVAL2          | 28.6651568             | Declination at the reference pixel                                         |
| CRPIX1          | -329.738223 [pixel]    | Reference pixel along axis 1                                               |
| CRPIX2          | 2945.36999 [pixel]     | Reference pixel along axis 2                                               |
| CD1_1           | -1.3972E-06            | Transformation matrix element                                              |
| CD1_2           | -9.2499E-05            | Transformation matrix element                                              |
| CD2_1           | -9.2444E-05            | Transformation matrix element                                              |
| CD2_2           | 1.3945E-06             | Transformation matrix element                                              |
| STDCRMS         | 0.0252604956907405     | Astrometric fit error (arcsec)                                             |
| MOONDIST        | 81.0                   | Distance to the moon in degrees                                            |
| MOONALT         | 18.29999923706055      | Altitude of the moon above the horizon                                     |
| MOONPHAS        | 83.40000152587891      | Phase of the moon                                                          |
| SKYLEVEL        | 252.99                 | Sky level                                                                   |
| SKYNOISE        | 10.96000003814697      | Sky noise                                                                   |
| PERCORR         | -0.05                  | Sky calibration correction (mags)                                          |
| MAGZPT          | 24.47                  | Uncorrected nightly ZP (per second)                                        |
| MAGZRR          | 0.02                   | Photometric ZP error (mags)                                                |
| EXTINCT         | 0.09                   | Extinction coefficient (mags)                                              |
| PHOTZP          | 28.2187 mag(Vega) = 2.5*log(pixel value) + PHOTZP |                          |
| PHOTZPER         | 0.03                   | Default 1-sigma PHOTZP uncertainty in IGAPS                                |
| PHOTSYS         | Vega                   | Photometric system                                                         |
| FLUXCAL         | IGAPS-UNIFORM          | Identifies the origin of PHOTZP                                             |
| SEEING          | 0.753579               | Average FWHM (arcsec)                                                      |
| ELLIPTIC        | 0.1319999992847443     | Average ellipticity                                                       |
| EXPTIME         | 30.07                  | [sec] Exposure time adopted                                                |
| CONFMAP         | iphas_jul2009          | r_conf.fits Confidence map                                                 |
| CHECKSUM        | ZjA6a53VdA3Zd53        | HDU checksum updated 2020-02-11T11:35:56                                    |
| DATASUM         | 1159687462             | data unit checksum updated 2020-02-11T11:35:56                             |