CROWDED FIELDS IN THE MILKY WAY AND BEYOND

C. Babusiaux[1,2]

[1]Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, B-1050 Bruxelles, Belgium
[2]Observatoire de Paris, GEPI / CNRS UMR 8111, 92195 Meudon Cedex, France

ABSTRACT

Although most of the sky will be almost empty to Gaia's high resolution eyes, several high density regions will be observed. They will present a challenge both for the on-board data handling and for the ground-based reduction, while being crucial for the Gaia science case. Indeed, the highest star densities are expected in the Galactic bulge low-extinction regions such as Baade's window, Galactic globular clusters and in the central regions of the Large Magellanic Cloud. I will present here those regions, their scientific impact and their observational complexity.

Key words: Gaia; Simulations; Galaxy: bulge; Globular clusters; Galaxies: Local Group.

1. INTRODUCTION

Most of the sky will be almost empty to Gaia's high resolution observations. The average sky density observed with Gaia will be of about 25 $\times$ 10^3 stars deg^{-2} up to $G \leq 20$ mag, the completeness limit of Gaia. However the stars are not distributed in an even way. The Galactic plane presents an average density of about 100 000 stars deg^{-2} for $|b| \leq 10°$ and $G \leq 20$ mag (ESA 2000). On smaller scales, from several degrees to arcminutes, the density can be much higher, exceeding a few million stars per square degree. The crowded fields will present a challenge both for the on-board data handling and for the on-ground reduction. We then need to characterize those fields and assess their observational difficulties and impact for the Gaia science case.

The crowding issue is fully dependent on the instrument and on the use of the observed data. I will then begin by presenting what is a crowded field for Gaia. Then I will show the different methods to detect those dense areas. In the following sections I will look in detail at the most crowded fields, namely the Galactic bulge low extinction regions, the globular clusters, and the nearby Galactic dwarf galaxies up to the distant but still resolved galaxies.

2. WHAT IS A CROWDED FIELD FOR GAIA?

Several definitions of a crowded field exist for Gaia, depending on the instruments spatial resolutions and magnitude limits and on the data acquisition and treatment.

Gaia will provide astrometry and photometry for each object up to magnitude $G = 20$ and radial velocities for the brighter objects up to about 17–18 mag. To this aim, Gaia has three different instruments: the Astrometric instrument (hereafter called Astro) which contains the astrometric fields and the broad-band photometer, and the medium band photometer (MBP) and the Radial Velocity Spectrometer (RVS) instruments. The MBP and the RVS are the two components of the Spectro instrument, with the same spatial resolution, but the dispersion of the spectra gives to the RVS a very different crowding limit, as we will see later on. The spatial resolution of a pixel of the Astro instrument is 44.2 mas $\times$ 132.5 mas, the best resolution being along the scanning direction of the satellite. This resolution is comparable to the HST Wide Field Planetary Camera pixel resolution. The pixel resolution of the Spectro instrument is much larger, $0.9'' \times 1.3''$, equivalent to typical ground-based resolution, although the PSF sampling will be much better. To lower the telemetry budget, the pixels are binned into samples. Only windows around the detected and selected objects will be transmitted to ground (Figure 1). In crowded fields several objects will be present in single windows. Gaia scanning continuously the sky in a Time-Delayed Integration mode, the relevant parameters for the on-board data handling crowding are the across-scan size of the individual CCDs ($4.3'$ in Astro, $44'$ in Spectro), the number of CCDs across-scan for the total CPU load (10 in Astro, 2 in Spectro) and the satellite scan rate (60 arcsec s^{-1}) to derive the time spent on crowded regions. In Astro the crowding will be increased by the fact that the two telescopes, separated by a basic angle of 99.4°, will have their images combined in the same focal plane.

The crowding limits will be different on-board and on-ground. On-board, the limits will be given by the data handling process and by the telemetry. The completeness of the catalogue will depend on the on-board detection, confirmation and selection processes (Arenou et al. 2005). It will then depend on the resolution of the samples read in the sky mappers, which are of 2 $\times$ 2 pixels

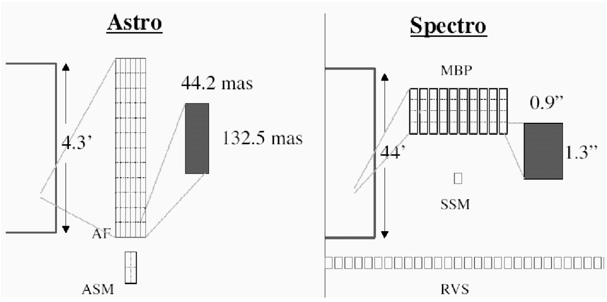

Figure 1. The main instrument resolution parameters that influence the definition of crowded fields for Gaia. a) the Astro instrument b) the Spectro instrument. On both figures are indicated, from left to right 1) the across-scan size of a CCD of the instrument, 2) the typical window sizes transmitted to ground around each selected object, 3) the pixel size.

in Astro (ASM) and one pixel in Spectro (SSM). Two other technical constraints apply to the selection limits: samples cannot overlap, and to lower the read-out noise a limit on the maximum number of samples that can be read in a single across-scan CCD line has to be set. On the telemetry point of view, it is the total amount of observations of all instruments at a given time that need to be taken into account, as presented by Lammers (2005). On-ground, all the different transits of the sources will be available (on average about 80 in Astro and 100 in Spectro), with different scan orientations. The combination of those transit images will allow the derivation of much higher resolution images (Dollet et al. 2005, Nurmi 2005). The increased signal-to-noise ratio will also increase the crowding due to stars fainter than the completeness limit.

There is therefore three main different angular scales that define a crowded region for Gaia. Large scale high density regions of tens of degrees will be an issue for the telemetry (namely the Galactic plane). For the on-board data handling (detection and selection) the highest density regions will be an issue, the relevant scale corresponding to an across-scan CCD size. For ground-based reduction study, crowding could be considered to begin as soon as two stars lie within the same window. The time scales of the occurrence of high density regions is also crucial for the on-board data handling: considering the Gaia scan rate and the total field of view across-scan of the instruments, a region of size s degrees traverses the Gaia focal plane in s minutes, and affects about s consecutive 6-hour scans in the Astro instrument (de Bruijne 2003a).

Several studies have been carried out to assess the instruments crowding limits. In the Astro and MBP instruments a maximum density limit had to be set to define the windowing and sampling strategy and design the on-board data handling. In Astro this limit has been computed assuming a worst case density of 3 million stars per square degree, corresponding to Baade's window described later on, for one telescope, plus a typical density of 150 000 stars deg^{-2}, corresponding to an average Galactic plane density, for the second telescope. This leads to a total crowding limit on the astrometric focal plane of 3.15 $\times$ 10^6 stars deg^{-2} up to G = 20 mag (de Bruijne 2003b). In MBP a limiting magnitude of G_S = 20.15 mag has been selected to satisfy the requirement that all stars observed in Astro are also observed in MBP (de Bruijne et al. 2004). The lower spatial resolution of MBP leads to crowding limits appearing at about 100 000 stars deg^{-2} for the on-board data handling. On-ground reduction of the MBP data using the accurate position information derived from Astro and PSF fitting photometry will lead to densities up to about 400 000 stars deg^{-2} attainable without significant degradation of the photometric precision (Evans 2004). In the RVS the crowding is a critical issue as it is a slitless spectrograph. No spectrum is free from superpositions of faint stars and overlaps between bright stars ($V < 17$ mag) will occur in about 20% of the spectra for a typical high Galactic latitude density of 1200 stars deg^{-2} for $V < 17$ mag (Zwitter & Henden 2003). Information recovery from overlapping spectra has been studied by Zwitter (2003) and a working value for the crowding limit of 20 000 stars deg^{-2} up to $G_S = 17$ mag is currently assumed by the RVS Working Group.

3. HOW TO DETECT THE DENSE AREAS?

There are two main ways to estimate the dense areas of the sky: using already available surveys or model simulations.

To be able to use a previous survey to estimate the source densities observed by Gaia, the survey should have magnitude limits and spatial resolutions better then Gaia. Such a survey covering the whole sky does not exist. The Guide Star Catalogue II (GSC-II) and the USNO-B catalogue provide an all-sky coverage up to about the Gaia completeness limit with a spatial resolution of 1 arcsec pixel^{-1}. Those catalogues therefore do answer the question of crowding for the on-board data handling and telemetry in the Spectro instrument. Such a study has been made by Drimmel et al. (2005) with the GSC-II catalogue. I will therefore concentrate in the following in the estimation of the crowding for the Astro instrument.

A theoretical sky model has the advantage of providing estimates of the sky densities up to the completeness limit regardless of the spatial resolution. Models also allow to simulate the fainter stars that will increase the noise budget, and provide for each source its intrinsic physical parameters which can be used to make realistic simulations of the photometric and spectral observations. The Besançon population synthesis model is currently used in the Universe model of the Simulation Working Group (Luri et al. 2005). It has been used also to derive the number of bulge stars that the different instruments of Gaia will be able to observe (Reylé et al. 2005). However a model, by definition, can be inaccurate. In particular for the low Galactic latitude fields, the extinction map is the main source of uncertainties (Robin et al. 2004). Indeed the extinction can be seen to vary on scales smaller than the arcminute and could present rather filamentary elongation. The stellar densities predicted by the Besançon model never reach the value of 3 million stars per square degree (Robin et al. 2004).

While the current available all-sky catalogues and models can be used to give the broad picture of the large-scale dense regions, their uncertainties in the relatively smaller scale regions of very high density are quite high, due respectively to their too low resolution and model uncertainties. Therefore we need to look for more point-like data observed with a higher resolution. In particular the Hubble Space Telescope provide observations with a pixel resolution equivalent to the Gaia astrometric field one. Indeed the HST Wide Field Planetary Camera 2 (HST-PC) has a resolution of 46 mas per pixel, but with a field of view of only 34 arcsec. The HST Advanced Camera for Surveys (ACS) WFC detectors have a resolution of 50 mas per pixel with a larger field of view of 100 arcsec. The ACS-HRC have a smaller field of view of 26 arcsec but with a higher angular resolution of 26 mas per pixel. Those data can then be used to look in detail at the most crowded regions that Gaia will observe. That's what will be presented in the following.

4. GALACTIC INNER BULGE LOW EXTINCTION REGIONS

The inner Galactic bulge is so highly obscured by dust in the optical that low extinction regions will be the main chance for Gaia to provide detailed observations of this population, crucial for our understanding of the Galaxy structure and evolution. In those regions Gaia will be able to derive red clump star parallaxes to a precision higher than 10–15% and observe bulge stars down to the main sequence turnoff (ESA 2000). The kinematics will allow the bulge dynamics, shape and mass to be mapped. The proper motions will also be used to discriminate foreground disc from bulge stars, which is crucial for those regions considering that about half of the stars observed are in fact disc stars (Paczynski et al. 1994).

Baade's window (Baade 1963) is the most famous low extinction inner bulge region. Situated at ($\ell = 1°$, $b = 4°$), it presents a high density of about 3 million stars per square degree up to G =20 mag on an area of 1 square degree. This high density region has been taken as a reference for the crowding limit in the Gaia astrometric instrument design. The final accuracies will be particularly difficult to obtain as it will be observed only a relatively low number of times due to the Gaia scanning law: 53 transits are predicted in Astro against a sky average value of 84 transits.

Several other low extinction regions have been detected in previous surveys. The closest to the Galactic plane are presented in Table 1 with their main characteristics (mainly from G. Bono, private communication). The closer fields to the Galactic centre which present the lower mean extinction values are Baade and SgrI windows. Therefore they are the best candidates for being the most crowded regions of the Galactic bulge. To derive the actual stellar densities that Gaia will observe in the Astro instrument in those regions, I used data kindly provided by K. Kuijken from HST-PC data up to V magnitudes fainter than 22 (Kuijken & Rich 2002). The derived densities are of 3.2 $\times$ 10^6 star deg^{-2} for Baade's window and 4.6 $\times$ 10^6 star deg^{-2} for SgrI window at $G < 20$ mag (Figure 3).

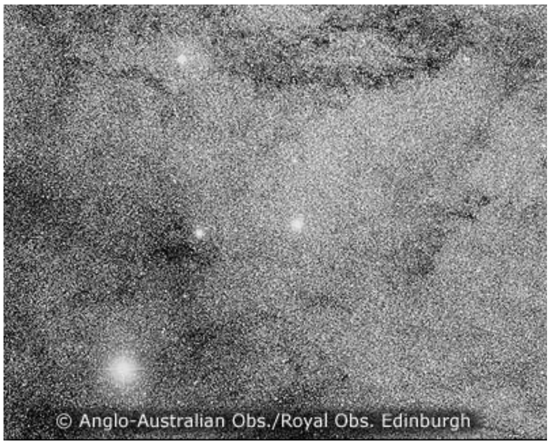

Figure 2. The on-board data handling worst nightmare. This is an image of Baade's window (width 1.5°). The two brightest spots at the centre are from left to right the globular clusters NGC 6528 and NGC 6522. The very bright spot at the bottom left is γ Sgr, a third magnitude star.

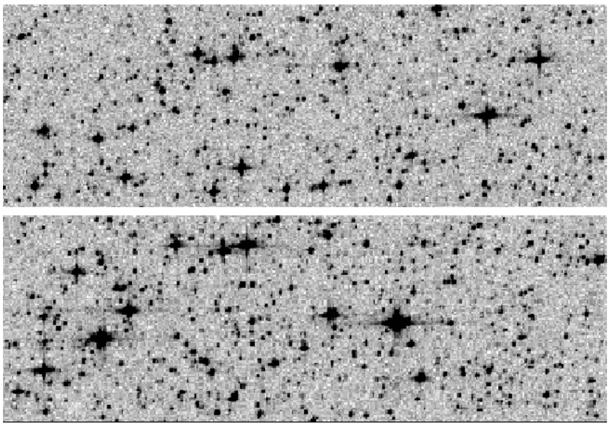

Figure 3. Gaia Astrometric sky mapper observations of a) Baade and b) SgrI windows, derived from HST-PC data of Kuijken & Rich (2002). The GIBIS image sizes are 32″× 32″

To check how representative the small field of view of the Baade and SgrI windows of Figure 3 are, I looked at the OGLE-II data (Udalski et al. 2002)[1]. Indeed the OGLE-II fields have a large field of view of 14′× 57′, corresponding to a full Spectro CCD across-scan size, with a resolution of 0.4 arcsec per pixel. Figure 4 shows that the HST-PC field of Kuijken & Rich (2002) does not seem peculiar. A similar tentative simulation of the SgrI OGLE field lead to an 'OutOfMemory error', confirming in a crude way that SgrI is indeed far more dense than Baade's window.

[1] The OGLE-II data are available from http://bulge.princeton.edu/∼ogle/ogle2/bulge_maps.html

Table 1. Galactic inner bulge low extinction regions. The mean optical absorption $< A_V >$ (in mag) is the extinction derived by Sumi (2004) in the OGLE field corresponding to the window.

name	l(°)	b(°)	area(° ²)	reference	$< A_V >$
Baade Window	1.0	−3.9	1	Baade (1963)	1.5
Sgr I Window	1.4	−2.6	1	Baade (1963)	2
Sgr II Window	4.1	−5.1	1.4	Baade (1963)	
Blanco Window I	0.6	−5.5	1.3	Blanco (1992)	
Blanco Window II	0.2	−5.8	0.8	Blanco & Blanco (1997)	
W0.2-2.1	0.2	−2.1	0.7	Stanek (1998)	3
W4.0+3.0	4.0	+3.0	5	Stanek (1998)	
W359.4-3.1	−0.6	−3.1	0.3	Dutra et al. (2002)	3
W2.0-3.3	2.0	−3.3	<0.3	Popowski et al. (2003)	1.5
W3.2-3.4	3.2	−3.4	<0.3	Popowski et al. (2003)	1.5
W3.9-3.8	3.9	−3.8	<0.3	Popowski et al. (2003)	2

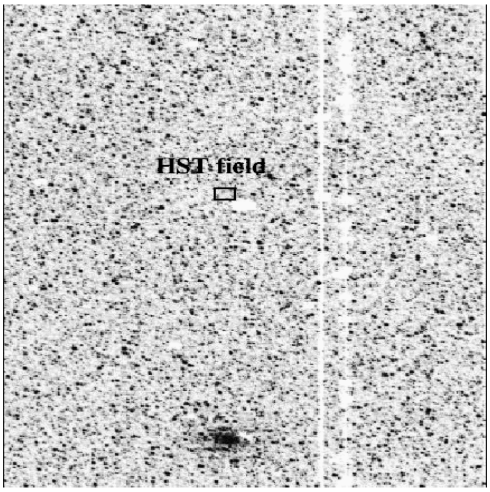

Figure 4. Spectro sky mapper observation of Baade's window from OGLE-II data (GIBIS image of 12′× 22′, half a CCD across-scan). The position of the HST field of Kuijken & Rich (2002) is overlaid. The cluster at the bottom is NGC 6522 (Figure 2).

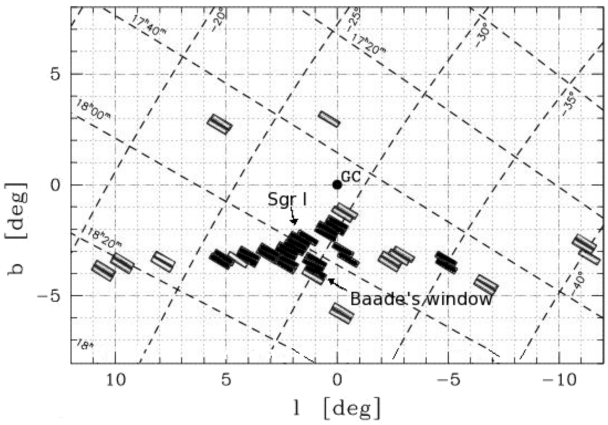

Figure 5. The OGLE-II bulge fields. The fields in black have a density higher than the field corresponding to Baade's window.

To look at how typical of the inner bulge fields Baade and SgrI windows are, I used again OGLE-II data. Figure 4 shows the 49 OGLE-II bulge fields. Half of them have a density higher than Baade's window. The OGLE field of SgrI window is indeed the one with the highest density of this survey, so that 4.6 × 10^6 star deg^{-2} up to $G = 20$ mag may be estimated as an upper limit to the relatively large scale high density regions of the inner Galactic bulge.

5. GLOBULAR CLUSTERS

Globular clusters are among the densest regions on the sky while being crucial for the Gaia science case. The Gaia astrometric capabilities on individual stars will allow member selection and internal dynamical studies, including cluster rotation and tidal effects. It will allow to derive very accurate distances and space motion of the clusters, constraining the Galactic gravitational potential, and provide much improved colour-magnitude diagrams. Strong constraints will therefore be provided on globular clusters formation and evolution. Globular clusters are also of first importance on the impact of Gaia on stellar astrophysics, as they are widely used as calibrators of stellar models thanks to the common properties in distance, age and metallicity of their members. As a consequence, even if those clusters can be observed with other instruments than Gaia thanks to their small area on the sky, it is crucial that they are observed with the highest precision possible with Gaia to provide not only an absolute calibration to their astrometry, but also an homogeneous sample of the photometry and astrometry that can be compared directly with the other stellar populations of the disc, halo, bulge, thick disc and Local Group galaxies.

There are about 150 Galactic globular clusters known so far. A data base of those clusters and their main parameters has been compiled by Harris (1996)[2]. According to the simulations presented in ESA (2000) from this data base (Figure 6), a vast majority of the clusters will present

[2] The Harris (1996) globular cluster data base is available at http://physwww.physics.mcmaster.ca/~harris/mwgc.dat

a density higher than 3 million stars per square degree within less than 1 arcminute radius from their centre. The core of those densest clusters not observed by Gaia will be covered by HST, NGST or SIM. Five clusters will have such extreme densities on larger scales, corresponding to more than 2 Astro CCDs across-scan field of view. One of them is the famous Omega Centauri, which is particularly important for the Gaia science case by the fact that is it suspected to be not a globular cluster but the core of a dwarf galaxy remnant. By its relatively low central density and close proximity, Omega Centauri is likely to be one of the easier clusters to observe. What Gaia will be able to observe on this cluster has been studied in Babusiaux et al. (2002).

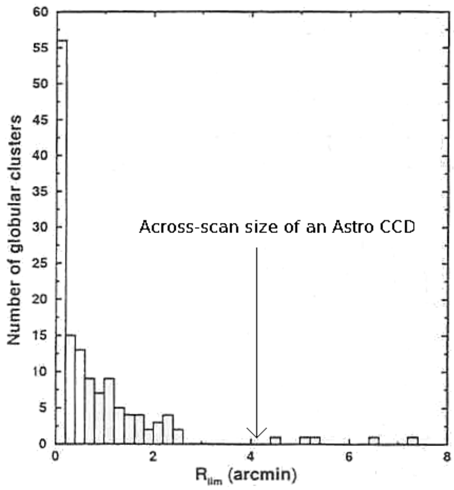

Figure 6. Distribution of the radii of the area over which the densities in Galactic globular clusters are larger than 3 million stars per square degree. Figure from ESA (2000). The across-scan size of an Astro CCD is indicated.

Globular clusters of dwarf galaxy satellites of the Milky Way will also be resolved by Gaia, in the Large (∼16) and Small (∼7) Magellanic Clouds and in the Sagittarius (∼6) and Fornax (5) dwarf spheroidals (numbers from Forbes et al. 2000 and Mackey & Gilmore 2004). However they are so far away that there will be no crowding problem expect for local on-ground reduction studies. Further away globular clusters will be detected as more or less extended bright objects and their measured astrometry will be used to derive the internal kinematics of their parent galaxy (e.g., M31 and M33 have respectively about 400 and 70 globular clusters, Forbes et al. 2000).

6. GALACTIC DWARF GALAXIES

There are 13 known dwarf companions to the Milky Way. The Gaia proper motions will allow discrimination between members and field stars and studies of the internal dynamics for the nearer dwarfs. The homogeneous photometric and astrometric sample obtained will allow direct comparison between the dwarfs galaxies and with the different stellar populations of the Milky Way.

The largest are the Large and Small Magellanic Clouds (Figure 7). They provide the nearest examples of young intermediate-to-low chemical abundances populations for study. Gaia will observe millions of stars in those galaxies, allowing a detailed study of their stellar populations and dynamical structures as well as the dynamical interactions LMC-SMC and LMC-Galaxy.

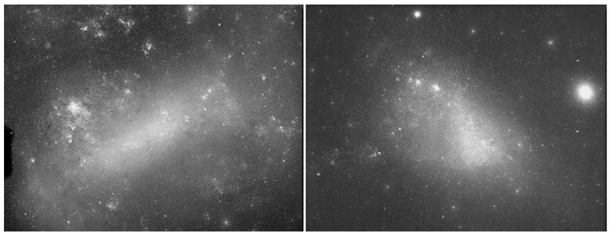

Figure 7. Images of the a) Large (width = 6°) and b) Small (width = 5.4°) Magellanic Clouds (Courtesy Anglo-Australian Obs./Royal Obs. Edinburgh).

The central bar of the LMC is one of the more extended regions with a very high stellar density that will be observed with Gaia. It has been estimated to present a density of 1.3 million stars per square degree using HST-PC data (Lindegren 1998), therefore fully accessible to the Astro instruments.

The more distant Galactic dwarfs will be fully observed even by the Spectro instruments. For example the central 4 arcminutes of Sculptor present a density of about 40 000 stars deg^{-2} up to $G_S = 20.15$ mag (number derived from ESO-WFI data kindly provided by M. Irwin).

7. DISTANT RESOLVED GALAXIES

Gaia will allow the mapping of the two-dimensional kinematic field of each resolved galaxy, allowing dynamical studies of those galaxies. In M31 and M33, described below, the detection of warp signatures are expected (ESA 2000). Although those galaxies can be observed by other instruments such as SIM, Gaia will measure a larger sample of stars and provide their absolute rather then relative proper motions.

For the more distant galaxies out of the Milky Way group, the crowding will not any more be an issue for the on-board data handling, although it will give some hard work to the on-board detection algorithm due to the very high and complex surface brightness of those galaxies. The on-ground reduction will however be largely affected by the crowding.

The Andromeda Galaxy (M31) is the closest large spiral galaxy. It has two bright dwarf companions M32 and M110 (Figure 8a). The Triangulum galaxy M33 is the third-largest Local Group disc galaxy, smaller and gravitationally bound to M31 (Figure 8b). Those galaxies will be the Local Group galaxies with the most stars resolved by Gaia out of the Milky Way sub-group, with more than 10^4 expected for M33 and even more for M31 (ESA 2000, Table 1.13). The bulge of M31 will present

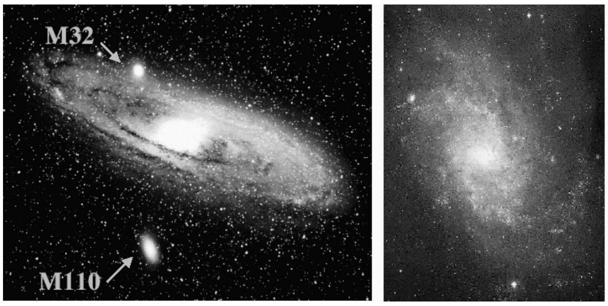

Figure 8. a) 3°× 1° image of M31. It includes its two bright dwarf elliptical companions: M32, of size ∼8′× 6′, and M110, of size ∼17′× 10′. b) 73′× 45′ image of M33 (Courtesy IAC/RGO/Malin).

particular difficulties for the on-board detection and on-ground reduction algorithms due to its large bulge surface brightness which presents a strong gradient.

Going further out of the Local Group, the galaxies will not be resolved in stars any more, although some globular clusters should be detected and therefore enable tracing of their kinematics. How Gaia will observe those galaxies is illustrated for M100, one of the brightest member galaxies of the Virgo Cluster, in Figure 9.

8. CONCLUSION

The most crowded fields for Gaia, exceeding the actual working value of the crowding limit in the Astro instruments of 3 million stars per square degree, will occur in a number of Galactic bulge low extinction regions and within the central parts of Galactic globular clusters. Among the highest densities observed with Gaia are in the Magellanic Clouds, up to about a million stars per square degree. Crowding in the Spectro instrument will occur in the Galactic plane (from about $|b| \leq 10°$).

Good observations will however still be obtained in the crowded regions for the brightest stars. The final accuracies that Gaia will achieve in those dense areas will depend on the on-board data handling, for the completeness of the catalogue and the number of observations available for each individual object, and on the on-ground data reduction for the final accuracies. To assess in detail the overall performances in dense fields, accurate simulations are needed. Most of the fields presented in this review are already available in the Gaia Instrument and Basic Image Simulator (Babusiaux 2005)[3]. They mostly come from simulations, HST-PC data or OGLE and ESO-WFI observations. But more data with very high resolution and wide fields of view are needed. Any contribution from you, the reader, would be highly appreciated![4].

[3]http://gibispc.obspm.fr/∼gibis
[4]Contact: carine.babusiaux@obspm.fr

ACKNOWLEDGMENTS

Thanks to G. Bono for providing a first table of the low extinction regions of the Galactic bulge and N. Robichon (Galactic globular cluster simulation), D. Mackey (HST-PC data of extragalactic globular clusters), M. Irwin (ESO-WFI data of Galactic dwarf spheroidals), M. Wilkinson and K. Kuijken (HST-PC data of Baade's and SgrI window) for providing their data.

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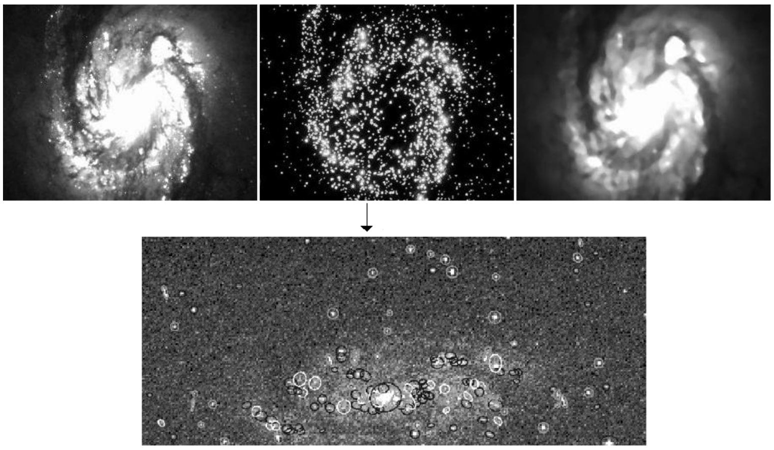

Figure 9. The M100 galaxy a) deconvolved from an original HST-PC image (1) into stars (2) and background (3) using StarFinder (Diolaiti et al. 2000) b) as observed in the Astro sky mappers, with the on-board detections overlaid. The images size are 32″× 32″.

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