The Galactic O-Star Spectroscopic Catalog (GOSC) and Survey (GOSSS): first whole-sky results and further updates

J. Maíz Apellániz\textsuperscript{1}, A. Sota\textsuperscript{1}, N. I. Morrell\textsuperscript{2}, R. H. Barbá\textsuperscript{3}, N. R. Walborn\textsuperscript{4}, E. J. Alfaro\textsuperscript{1}, R. C. Gamen\textsuperscript{5}, J. I. Arias\textsuperscript{3}, and A. T. Gallego Calvente\textsuperscript{1}

\textsuperscript{1} Instituto de Astrofísica de Andalucía-CSIC, Granada, Spain
\textsuperscript{2} Las Campanas Observatory, La Serena, Chile
\textsuperscript{3} Departamento de Física, Universidad de La Serena, La Serena, Chile
\textsuperscript{4} Space Telescope Science Institute, Baltimore, MD, USA
\textsuperscript{5} Instituto de Astrofísica de La Plata (CONICET, UNLP), La Plata, Argentina

Abstract

The Galactic O-Star Spectroscopic Survey (GOSSS) is obtaining high quality $R \sim 2500$ blue-violet spectroscopy of all Galactic stars ever classified as of O type with $B < 12$ and a significant fraction of those with $B = 12 - 14$. As of June 2013, we have obtained, processed, and classified 2653 spectra of 1593 stars, including all of the sample with $B < 8$ and most of the sample with $B = 8 - 10$, making GOSSS already the largest collection of high quality O-star optical spectra ever assembled by a factor of 3. We discuss the fraction of false positives (stars classified as O in previous works that do not belong to that class) and the implications of the observed magnitude distribution for the spatial distribution of massive stars and dust within a few kpc of the Sun. We also present new spectrograms for some of the interesting objects in the sample and show applications of GOSSS data to the study of the intervening ISM. Finally, we present the new version of the Galactic O-Star Catalog (GOSC), which incorporates the data in GOSSS-DR1, and we discuss our plans for MGB, an interactive spectral classification tool for OB stars.

1 A history of the project

- 2004: v1.0 of the Galactic O-Star Catalog (GOSC, Maíz Apellániz et al.\textsuperscript{2004}).
  - Literature spectral types (mostly 1970-80s by N. R. Walborn).
  - Additional data from different sources.
• 2006: v2.0 of GOSC with many more stars (Sota et al., 2008).

• 2007: GOSSS starts based on GOSC.
  - $R \sim 2500$, uniform quality blue-violet spectroscopy.
  - Both hemispheres, complete to a given B magnitude.
  - Revised spectral types for Galactic O stars.

• 2010: First letter on Ofc and O?p stars (Walborn et al., 2010).

• 2011: First paper with bright northern stars, complete set of standards, and revised classification criteria (Sota et al. 2011, paper I).

• 2011: Survey description (Maíz Apellániz et al. 2011).

• 2012: Second letter on OUn stars (Walborn et al., 2011).

• 2012: GOSSS data used for NGC 1624-2 (Wade et al., 2012) and HD 120 678 (Gamen et al., 2012) papers.
2 What is new?

- A second paper with bright southern stars is about to be submitted (Sota et al. 2013b).
- Spectral types and spectra for all the stars in the first two papers have been made public as Data Release 1 (GOSSS-DR1, Sota et al. 2013a in these proceedings).
- GOSC has been remodelled (v3.0) to include the above.
- First whole-sky results have been obtained.
- GOSSS is now being used to study the Diffuse Interstellar Bands (DIBs) in the intervening ISM (Maíz Apellániz et al. 2013).
- MGB, the accompanying spectral classification software (Maíz Apellániz et al. 2012), will be released with GOSSS-DR2.
3 GOSC v3.0

- Now based on GOSSS-DR1:
  - 449 stars with spectral types from GOSSS papers I and II.
  - Alternate and previous spectral types as additional columns.
  - Revised approximate $B$ and $J$ photometry ($B_{ap}$, $J_{ap}$) for all stars. Most of the $J_{ap}$ values are taken from 2MASS with a few exceptions. The $B_{ap}$ values are either Tycho-2 or Johnson and are, in general, less uniform than the $J_{ap}$ ones. All the values have been rounded up to one tenth of a magnitude in order not to overestimate their accuracy. In those cases where the WDS catalog (Mason et al., 2001) lists more than one visual component, the $B_{ap}$ and $J_{ap}$ photometry refers to the brightest component included in the spectrum (with the flux partition derived from the WDS $\Delta m$). This photometry can be used to estimate the color excess $E(B-J)$ knowing that $(B-J)_0$ ranges between $-0.7$ and $-1.0$ for O stars. $E(B-J)$ has the advantage over $E(B-V)$ of exploiting a longer baseline in wavelength (thus being more accurate when using diverse sources) and is preferred over $E(B-K)$ because $K$-band photometry may be affected by IR excesses. Also, $E(B-J) \sim A_V$ for the most common extinction laws.
  - Revised WDS (Mason et al., 2001) membership.
Figure 4: Four examples of false positives: B stars that were previously classified as being of O type by Muzzio & McCarthy (1973), Feinstein et al. (1980), Garrison et al. (1977), and Garmany et al. (1982), respectively.

- Direct access to GOSSS spectra (FITS tables).

- Future:
  - New GOSSS data releases: O, WR, and other early-type stars: ~2500 objects planned by 2016.
  - LMC+SMC extension.
  - CHORIZOS-derived SEDs (Maiz Apellániz 2004) using the new family of extinction laws of Maiz Apellániz (2013).
  - Additional interface improvements.

Visit [http://gosc.iaa.es](http://gosc.iaa.es)
4 First whole-sky results of GOSSS

4.1 New spectral classifications

- They include all bright Galactic O stars (those with $B_{ap} \leq 8.0$) and dimmer objects.

- Some bright O stars are “new” in the sense that most or all of the previous classifications were of B type (see Figure 1). For example, I Cep AaAbB (HD 202 214 AaAbB), O9.5 IV, is likely a composite spectrum, since it has three visual bright components (unresolved in GOSSS-DR1). It has at least ten previous spectral classifications as B0 (including Morgan et al. 1953 and Lesh 1968) but we have found only one as O9 (Mannino & Humblet, 1955).

- HD 93 632 was classified as O5 III (f)var by Walborn 1973 but in Figure 2 it clearly has a luminosity class of I, based on He II λ4686 strongly in emission. Recent OWN spectra (Barbá et al. 2010) show a weaker He II λ4686, indicating unusual variability, possibly related to the presence of a magnetic field.

- CPD −47 2962 is one of many new members of the O Vz class discovered with GOSSS (Figure 2).
ALS 15 204 is a serendipitous discovery: it was placed on the slit because another O star was observed nearby (Figure 2). A weak redward component may indicate the presence of a dim spectroscopic B companion.

HD 124 314 A and BaBb are separated by 2″ and both have O spectral types (Figure 3). Ba and Bb cannot be separated in GOSSS-DR1 as they are only 0″21 apart. A is a likely SB system according to preliminary OWN results ([Barba et al. 2010]) but is not seen as such here.

HD 93 161 A and B are separated by 2″ and both are O-type systems (Figure 3). HD 93 161 A itself is an O+O spectroscopic binary.

4.2 Lies, damn lies, and statistics

We have observed 1593 stars, which in the literature appeared as:

- O: 1014.
- B or OB: 382.
- Other: 93.
- No previous classification: 104.
Of those 1593 stars, 799 turned out to be real O stars. The false positives (objects that went from O to non-O) were 252, yielding a false positive rate of 252/1014 = 24.9%. Examples are found in Figures 4 and 5. Figure 6 shows the dependence with $B$ magnitude. The false positives were of spectral type:

- A: 4.
- B: 213.
- F: 14.
- G: 5.
- K: 7.
- LBV: 1.
- PN: 4.
- sd: 4.

The false negatives (objects that went from non-O to O) were 37, yielding a false negative rate of 37/579 = 6.4%. Those stars were previously classified as:

- B: 28.
- OB: 2.
- WR: 1.
- No previous classification: 6.

4.3 How many O stars are there in the solar neighborhood?

- Toy model to compare observations:
  - Constant surface density of O stars in the Galaxy.
  - Disk with a 12 kpc radius.
  - Sun at 8 kpc from the center.
  - Constant extinction per unit distance ($A_V$/kpc) and standard extinction law with $R_{5405} = 3.1$.
  - Kroupa IMF, Geneva non-rotating evolutionary tracks, and constant star formation rate.

- Data:
Figure 7: Empirical magnitude histograms and toy-model predictions. The histograms ($B_{ap}$, left panel; $J_{ap}$, right panel) show the confirmed and estimated (from the unobserved part of the GOSSS sample) magnitude distributions for O stars. Predictions for four cases of our toy model with different values of the surface density and the extinction per unit distance are also shown.

- GOSSS stars already observed and classified.
- Resolved O stars counted individually but SB2 O+O systems counted as a single object.
- Prediction on the expected number from candidates and previous rates of false positives and false negatives.

**Results (Figure 7):**

- $B_{ap}$ distribution is consistent with either low surface density + extinction per unit distance or high surface density + extinction per unit distance.
- $J_{ap}$ distribution favors the large values of surface density and extinction per unit distance.
- The effect of the Local Bubble and our interarm location creates a dearth of NIR-bright ($J_{ap} < 5$) stars. This effect is also seen in the spatial distribution derived from Hipparcos parallaxes [Maíz Apellániz 2001, Maíz Apellániz et al. 2008].
- 30-40 O stars/kpc$^2$ corresponds to 14 000-18 000 O stars in the Milky Way if the toy model holds throughout the whole Galaxy.
- $A_V$ per unit distance appears to be 0.6-0.8 mag/kpc but patchy extinction may be unseen in the data.
- When all effects are considered (radial density gradient in the Galaxy, spectroscopic binaries, patchy extinction), the real number of O stars in the Galaxy may be larger by a factor of 2 or 3 (30 000-50 000).
Figure 8: Two examples of DIBs observed with GOSSS using the pair method of combining pairs of stars of the same spectral type, one with high extinction and one with low extinction. The error bars show the average and standard deviation for six (left panel) or seven (right panel) pairs and the red line the Gaussian fit. The 4591 Å DIB is clearly detected for the first time and it has the correct wavelength for the Ehrenfreund et al. (1995) prediction for coronene and ovalene cations. In the second case (the region adjacent to H\(\beta\)) we detect that the broad DIB has two components, shown with dotted blue and green lines, respectively. The large error bars around 4860 Å are caused by the subtraction of H\(\beta\).

- We will recalculate this with a more sophisticated model at the end of the project.

5 Diffuse Interstellar Bands with GOSSS

- Why use long-slit intermediate resolution spectroscopy to study DIBs (as opposed to échelle spectroscopy)?

- Advantages:
  - Broad DIBs more clearly seen than in échelle data.
  - Deeper magnitudes reached when all things equal.
  - Can do two (or even three) stars at a time.

- Disadvantages:
  - Worse spectral resolution (e.g. no kinematics or structure in narrow DIBs).
  - Harder to detect weak narrow DIBs.
  - Smaller spectral coverage in a single setting.
Figure 9: Example of fitting an SB2 system with MGB. Eight parameters can be adjusted: the spectral types, luminosity classes, and velocities of both the primary and secondary, the flux fraction of the secondary, and the rotation index n. Here HD 93 161 A (black) is fitted with a combination (red) of 60% of HD 152 590 and 40% of 10 Lac. See also Figure 3.

- See Figure 8 and Maíz Apellániz et al. (2013) for some results.

6 MGB

- Interactive spectral classification tool for OB stars (Maíz Apellániz et al., 2012).
- Uses GOSSS library of standard stars at $R \sim 2500$.
- Includes fitting of SB2 systems (see Figure 9 for an example) and rotation index n.
- Modular: other libraries can be used (e.g. $R \sim 4000$).
- It will be included in GOSSS-DR2.

Acknowledgments

Support for this work was provided by [a] the Spanish Government Ministerio de Ciencia e Innovación through grants AYA2007-64052, AYA2007-64712, AYA 2010-17631, AYA 2010-15081, the Ramón y Cajal Fellowship program, and FEDER funds; [b] the Junta de Andalucía grant P08-TIC-4075; [c] NASA through grants GO-10205, GO-10602, and GO-10898 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy Inc., under NASA contract NAS 5-26555; [d] the Dirección de Investigación de la Universidad de La Serena (DIULS PR09101); [e] the ESO-Government of Chile Joint Committee Postdoctoral Grant; and [f] the Chilean Government grants FONDECYT Regular 1120668 and FONDECYT Iniciación 11121550. This research has made extensive use of [a] Aladin (Bonnarel et al., 2000); [b] the SIMBAD database, operated at CDS, Strasbourg, France; and [c] the Washington Double Star Catalog, maintained at the U.S. Naval Observatory (Mason et al., 2001). We would like to thank Miguel Penadés Ordaz for his help in the compilation of data for this work.
References

Barbá, R. H., Gamen, R. C., Arias, J. I., Morrell, N. I., Maíz Apellániz, J., Alfaro, E. J., Walborn, N. R., & Sota, A. 2010, in Rev. Mex. Astron. Astrofís. (conference series), Vol. 38, 30

Bonnarel, F., et al. 2000, A&AS, 143, 33

Conti, P. S., & Alschuler, W. R. 1971, ApJ, 170, 325

Ehrenfreund, P., Foing, B. H., D’Hendecourt, L., Jenniskens, P., & Desert, F. X. 1995, A&A, 299, 213

Feinstein, A., Moffat, A. F. J., & Fitzgerald, M. P. 1980, AJ, 85, 708

Gamen, R., Arias, J. I., Barbá, R. H., Morrell, N. I., Walborn, N. R., Sota, A., Maíz Apellániz, J., & Alfaro, E. J. 2012, A&A, 546, A92

Garmany, C. D., Conti, P. S., & Chiosi, C. 1982, ApJ, 263, 777

Garrison, R. F., Hiltner, W. A., & Schild, R. E. 1977, ApJS, 35, 111

Hiltner, W. A. 1956, ApJS, 2, 389

Lesh, J. R. 1968, ApJS, 17, 371

Maíz Apellániz, J. 2001, AJ, 121, 2737

Maíz Apellániz, J. 2004, PASP, 116, 859

Maíz Apellániz, J. 2013, in Highlights of Spanish Astrophysics VII, 583

Maíz Apellániz, J., Alfaro, E. J., & Sota, A. 2008, arXiv:0804.2553

Maíz Apellániz, J., et al. 2012, in Astronomical Society of the Pacific Conference Series, Vol. 465, Astronomical Society of the Pacific Conference Series, ed. L. Drissen, C. Rubert, N. St-Louis, & A. F. J. Moffat, 484

Maíz Apellániz, J., Sota, A., Barbá, R. H., Morrell, N. I., Pellerin, A., Alfaro, E. J., & Simón-Díaz, S. 2013, arXiv:1305.6163

Maíz Apellániz, J., Sota, A., Walborn, N. R., Alfaro, E. J., Barbá, R. H., Morrell, N. I., Gamen, R. C., & Arias, J. I. 2011, in Highlights of Spanish Astrophysics VI, ed. M. R. Zapatero Osorio, J. Gorgas, J. Maíz Apellániz, J. R. Pardo, & A. Gil de Paz, 467

Maíz Apellániz, J., Walborn, N. R., Galué, H. Á., & Wei, L. H. 2004, ApJS, 151, 103

Mannino, G., & Humblet, J. 1955, Annales d’Astrophysique, 18, 237

Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466

Morgan, W. W., Whitford, A. E., & Code, A. D. 1953, ApJ, 118, 318

Muzzio, J. C., & McCarthy, C. C. 1973, AJ, 78, 924

Schild, R. E., Neugebauer, G., & Westphal, J. A. 1971, AJ, 76, 237
Sota, A., Maíz Apellániz, J., Walborn, N. R., Alfaro, E. J., Barbá, R. H., Morrell, N. I., Gamen, R. C., & Arias, J. I. 2011, ApJS, 193, 24

Sota, A., Maíz Apellániz, J., Walborn, N. R., & Shida, R. Y. 2008, in Rev. Mex. Astron. Astrofis. (conference series), Vol. 33, 56

Wade, G. A., et al. 2012, MNRAS, 425, 1278

Walborn, N. R. 1973, AJ, 78, 1067

Walborn, N. R., Maíz Apellániz, J., Sota, A., Alfaro, E. J., Morrell, N. I., Barbá, R. H., Arias, J. I., & Gamen, R. C. 2011, AJ, 142, 150

Walborn, N. R., Sota, A., Maíz Apellániz, J., Alfaro, E. J., Morrell, N. I., Barbá, R. H., Arias, J. I., & Gamen, R. C. 2010, ApJL, 711, L143