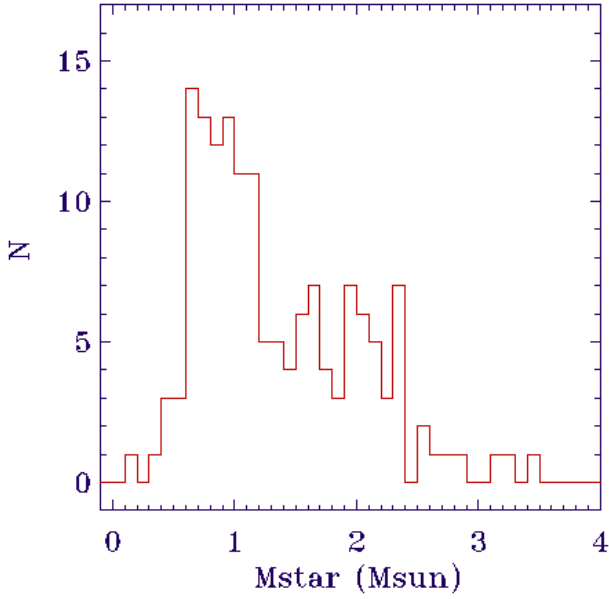
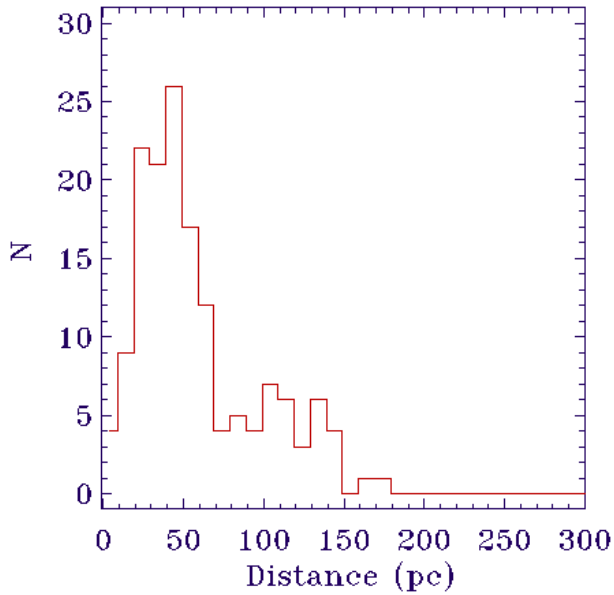




|                                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
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| <b>Publication Year</b>          | 2021                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| <b>Acceptance in OA</b>          | 2022-03-16T16:56:40Z                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| <b>Title</b>                     | The SPHERE infrared survey for exoplanets (SHINE). I. Sample definition and target characterization                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| <b>Authors</b>                   | DESIDERA, Silvano, Chauvin, G., Bonavita, M., MESSINA, Sergio, LeCoroller, H., SCHMIDT, TOBIAS MARIUS, GRATTON, Raffaele, Lazzoni, C., Meyer, M., Schlieder, J., Cheetham, A., Hagelberg, J., Bonnefoy, M., Feldt, M., Lagrange, A. -M., Langlois, M., Vigan, A., Tan, T. G., Hamsch, F. -J., Millward, M., ALCALA', JUAN MANUEL, BENATTI, SERENA, Brandner, W., Carson, J., COVINO, Elvira, Delorme, P., D'ORAZI, VALENTINA, Janson, M., RIGLIACO, ELISABETTA, Beuzit, J. -L., Biller, B., Boccaletti, A., Dominik, C., Cantalloube, F., Fontanive, C., Galicher, R., Henning, Th., Lagarde, E., LIGI, ROXANNE, Maire, A. -L., Menard, F., MESA, DINO, Müller, A., Samland, M., Schmid, H. M., Sissa, E., TURATTO, Massimo, Udry, S., Zurlo, A., Asensio-Torres, R., Kopytova, T., Rickman, E., Abe, L., Antichi, J., BARUFFOLO, Andrea, Baudoz, P., Baudrand, J., Blanchard, P., Bazzon, A., Buey, T., Carbillet, M., Carle, M., Charton, J., CASCONI, Enrico, CLAUDI, Riccardo, Costille, A., Deboulb , A., DE CAPRIO, VINCENZO, Dohlen, K., FANTINEL, Daniela, Feautrier, P., Fusco, T., Gigan, P., GIRO, Enrico, Gisler, D., Gluck, L., Hubin, N., Hugot, E., Jaquet, M., Kasper, M., Madec, F., Magnard, Y., Martinez, P., Maurel, D., Le Mignant, D., M ller-Nilsson, O., Llored, M., Moulin, T., Orign , A., Pavlov, A., Perret, D., Petit, C., Pragt, J., Puget, P., Rabou, P., Ramos, J., Rigal, F., Rochat, S., Roelfsema, R., Rousset, G., Roux, A., SALASNICH, Bernardo, Sauvage, J. -F., Sevin, A., Soenke, C., Stadler, E., Suarez, M., Weber, L., Wildi, F. |
| <b>Publisher's version (DOI)</b> | 10.1051/0004-6361/202038806                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>Handle</b>                    | <a href="http://hdl.handle.net/20.500.12386/31639">http://hdl.handle.net/20.500.12386/31639</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| <b>Journal</b>                   | ASTRONOMY & ASTROPHYSICS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| <b>Volume</b>                    | 651                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |



**Fig. 2.** Histogram of stellar masses for the F150 sample.

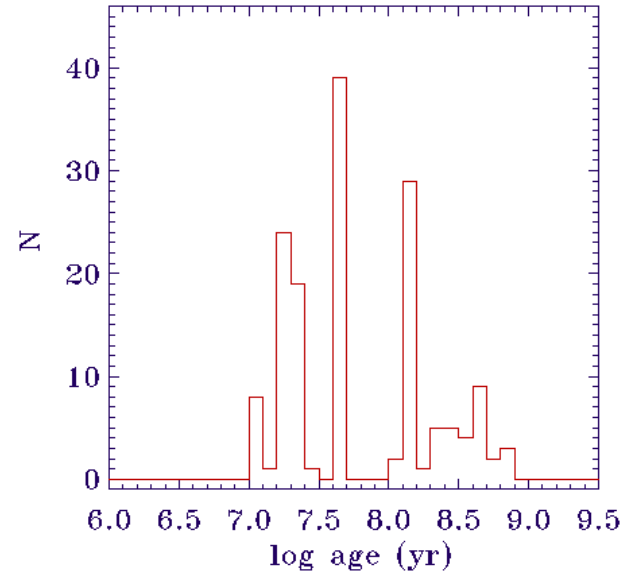


**Fig. 3.** Histogram of distances for the F150 sample.

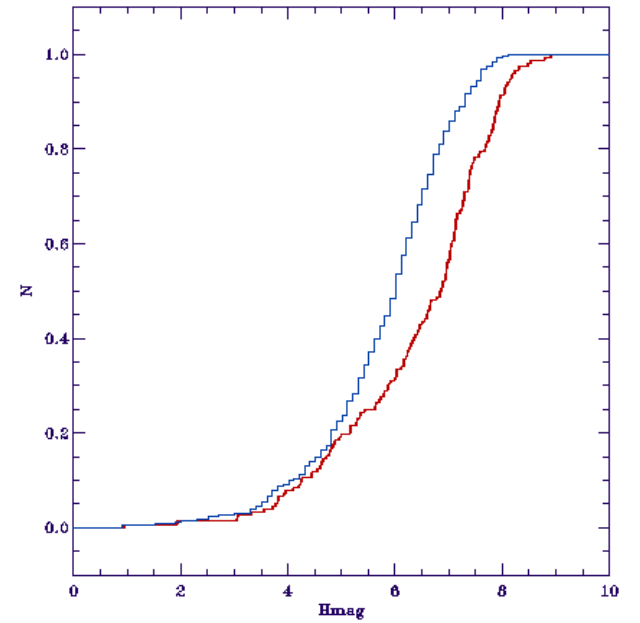
selection process (Table 11), although improved thanks to the availability of data on individual targets and better ages of the MGs. Only in a handful of cases were the revised ages found to be  $>1$  Gyr. These targets were removed from the present work, being old interlopers in the original sample (tidallylocked binaries, Li-rich giants, or stars with badly measured age indicators; details will be provided in forthcoming works).

The median mass is  $1.15 M_{\odot}$ , with 90% limits of  $0.57$  and  $2.37 M_{\odot}$ . Most of the early-type stars (mass  $\geq 1.5 M_{\odot}$ ) are members of Sco-Cen groups. The broad mass range of the sample will allow us to investigate in Paper III the mass dependence of the frequency and properties of substellar companions. The analysis will be extended to higher stellar masses by the BEAST survey, targeting B-type stars in Sco-Cen (Janson et al. 2019).

The median distance is 48 pc, with 90% limits of 11 and 137 pc. The peak in the distance distribution between 100 and 150 pc is due to the inclusion of Sco-Cen members. At 150 pc,



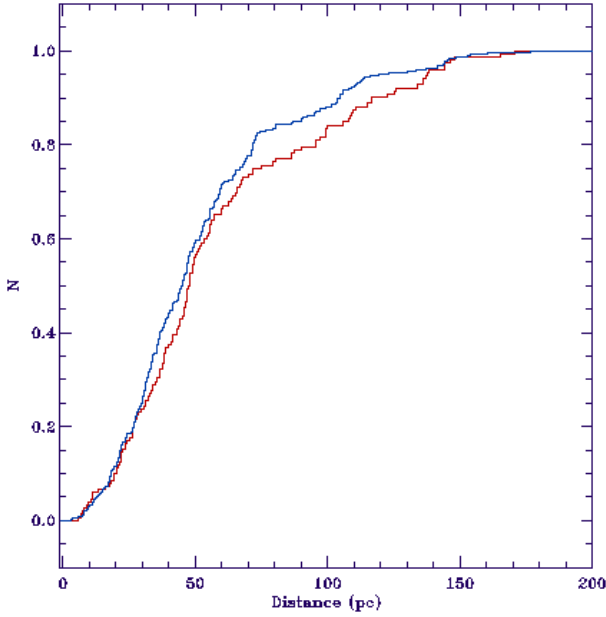
**Fig. 4.** Histogram of stellar ages for the F150 sample.



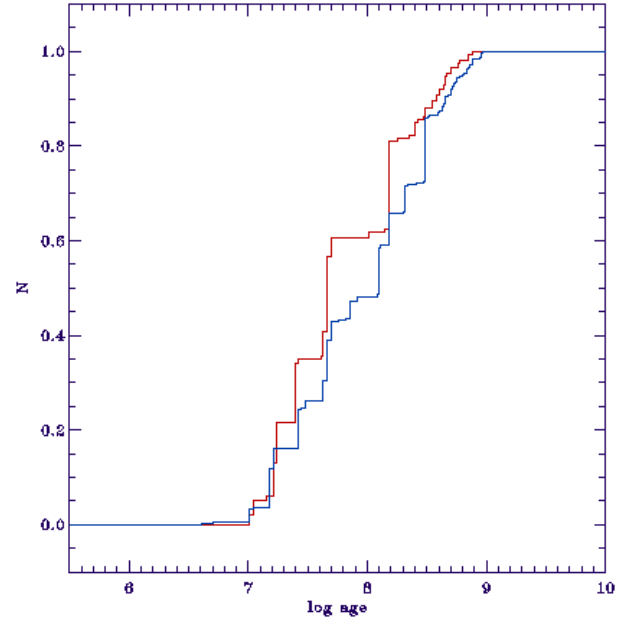
**Fig. 5.** Cumulative distribution of  $H$ -band magnitude for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).

the inner working angle of SPHERE allows us to access separation of  $\geq 20$  au for the presence of planetary companions.

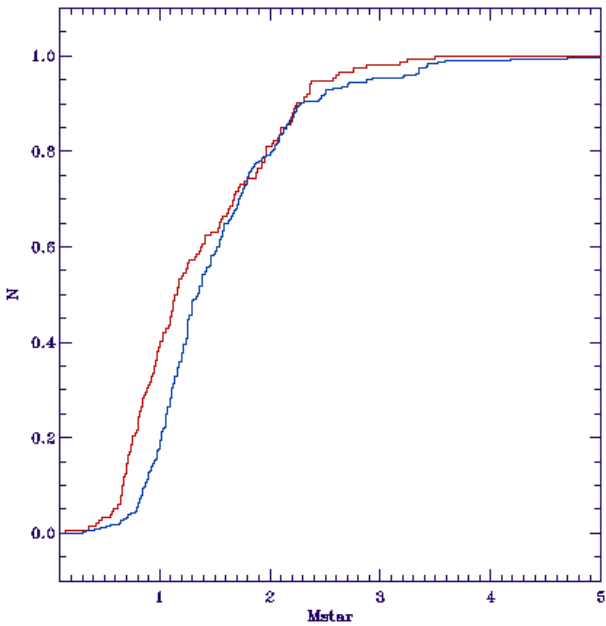
The stars with resolved disks and detectable IR excess have a different mass distributions with respect to those without these features, being more massive (median values  $1.41$  versus  $0.94 M_{\odot}$ ), while the age distributions of stars with and without disks are similar. Considering the inhomogeneity of our census of disks concerning, for example, the wavelengths of the observations, sensitivity to IR excess with respect to the stellar photosphere, and sensitivity to spatially resolved disks, we do not investigate the origin of these features. While our original survey sample has no specific biases linked to the presence of disks or IR excess, which were never considered in the selection process, some of the stars with disks were observed with increased priority because of the presence of the disks themselves (see



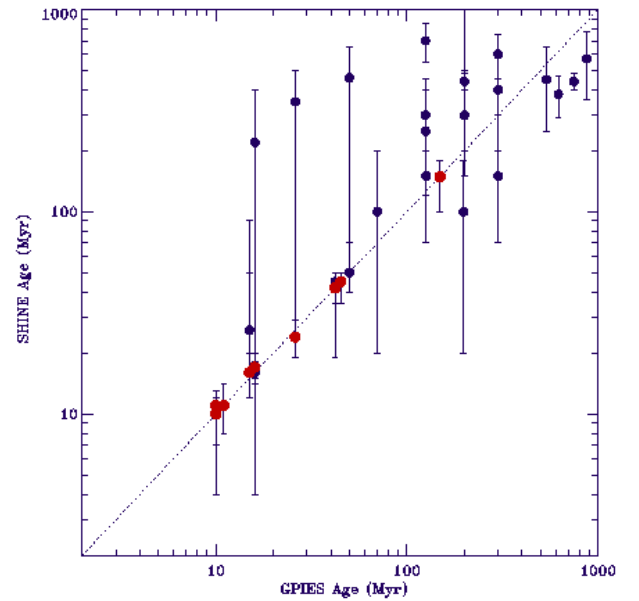
**Fig. 6.** Cumulative distribution of distance for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).



**Fig. 8.** Cumulative distribution of log(age) for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).



**Fig. 7.** Cumulative distribution of masses for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).



**Fig. 9.** Comparison of ages derived in the present work and in Nielsen et al. (2019). Black circles refer to individual stars and red circles to moving groups (typically several targets for each group). The error bars refer to the minimum and maximum age values from Table 9.

Sect. 3.2). This effect will be mitigated by the end of the survey, allowing more robust statistical inferences.

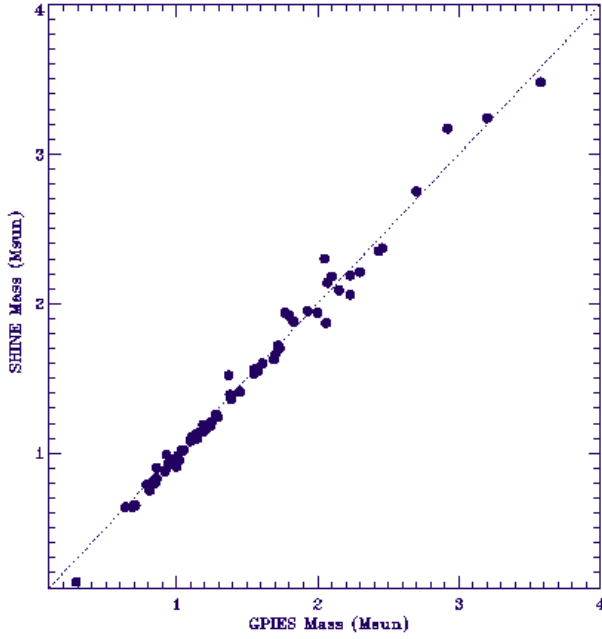
As already noted in Vigan et al. (2017), the majority of young nearby stars have metallicity values close to solar, making the sample of stars searched for planets via direct imaging somewhat different with respect to those considered by RVs and transits, which span a broader range of age and metallicity. The available data (e.g., Viana Almeida et al. 2009) suggest a slightly subsolar metallicity for stars in nearby young associations, at odds with expectations from galactic chemical evolution models. Recent results indicate that the standard chemical abundance analysis might be biased for young stars, because of an overestimation of microturbulent velocities somewhat linked to stellar activity

(Reddy & Lambert 2017; Baratella et al. 2020; Spina et al. 2020). Since a new analysis of chemical composition of members in various moving groups with these new methods is not yet available, we assumed in the following a solar metallicity for all the targets.

## 6.2. Comparison with GPIES and other surveys

### 6.2.1. Properties of individual targets

In the F150 sample, 67 out of 150 stars were also observed with GPI and were included in the GPIES early statistical analysis (Nielsen et al. 2019). In Fig. 9 we compare the adopted ages; 49 of the 67 overlapping targets are members of moving groups,



**Fig. 10.** Comparison of stellar masses derived in the present work and in Nielsen et al. (2019).

for which the adopted individual age is equal (TW Hya,  $\eta$  Cha, Tuc-Hor, Columba, Carina, Argus, AB Dor MG) or differ by a very small amount, 1 or 2 Myr ( $\beta$  Pic MG, Sco-Cen groups). As a result, the median age difference is equal to zero, and we can infer that the age scales in the two studies are very similar. Nevertheless, there are moderately large discrepancies for some individual field objects, for which ages are more uncertain. In a few cases for which the membership to groups is ambiguous (see Appendix A for details on individual objects), we adopted the stellar age derived independently of the group membership constraints (typically much older than the group ages) with lower limits encompassing the group ages. In most of these cases, Nielsen et al. (2019) adopted the membership to the groups and the corresponding ages, resulting in fairly large discrepancies. We also note that the ages adopted in Nielsen et al. (2019) for the components in the Fomalhaut system (749 Myr for A and 200 Myr for B) bracket our adopted common value for the system (440 Myr).

The comparison of the adopted masses in Fig. 10 also shows fairly good agreement over the whole range of masses considered by the programs. There is a small systematic difference, median delta of  $0.03 M_{\odot}$  with our masses being smaller. There is perfect agreement for the adopted distances, derived from the same sources (*Gaia* DR2 and HIPPARCOS).

### 6.2.2. Sample comparison

After the comparison of the individual stellar parameters, we compared the distributions, in order to reveal differences between the two samples. A first highly significant difference concerns the stellar magnitude (Fig. 5). This can be understood due to the differences between the AO systems of GPI and SPHERE, the latter working well to fainter magnitudes. This allowed us to choose a fainter magnitude limit. As a result, our sample includes a larger fraction of low-mass stars and extends to slightly larger distances (Fig. 6). The median masses of SHINE-F150 and GPIES being  $1.15$  and  $1.34 M_{\odot}$ , respectively, with stars below  $1 M_{\odot}$  representing 40% of the sample for SHINE and just

19% for GPIES (Fig. 7). Additional differences concern the high-mass tail, where we stopped at about  $3 M_{\odot}$ . There are only three stars with masses higher than this value in our final determination, (i.e., 2% of the sample, with a maximum value of  $3.48 M_{\odot}$ ). On the other hand, GPIES extends up to  $9 M_{\odot}$  with 4.5% of the targets more massive than  $3 M_{\odot}$ .

There are also some differences in the age distribution (median ages of 45 Myr for SHINE and 125 Myr for GPIES, Fig. 8). The age difference is mostly explained by the larger fraction of field early-type stars (typically intermediate age) in the GPIES sample and by the larger fraction of young low-mass MG members in our sample, due to the fainter magnitude limit.

Both teams avoided close visual binaries within the field of view of the high-contrast instruments. As the field of view of GPIES is smaller with respect to SHINE/SPHERE, binaries with 3–6 arcsec projected separation, not present in our sample, are included in GPIES. Finally, GPIES included in their statistics a sample of spatially unresolved binaries. The corresponding planets searched in these systems are circumbinary. Instead, we excluded these systems from the present study, although unrecognized spectroscopic binaries might still be present because of the lack of RV monitoring for a fraction of our targets. As spectroscopic binaries represent about 10% of the GPIES sample, this difference could have some impact on the statistical results.

## 7. Summary and conclusions

We described SHINE, the largest direct imaging survey for exoplanets at VLT performed as part of SPHERE GTO. We detailed the process of sample selection and the priority ranking scheme. The survey is focused on young nearby stars, with spectral types from A to M. Known binaries within the field of view of the SPHERE-IRD camera (6 arcsec) are excluded, as are all known spectroscopic binaries (though not all targets were thoroughly searched).

A subsample of 150 stars with first epoch observations done before February, 2017 was defined for a preliminary statistical assessment of the frequency of planets and brown dwarfs in wide orbits (5–300 au). This paper presents the characterization of the individual targets and of this subsample as a whole. The companion paper (Langlois et al. 2021) presents the observations, data processing, identification, and classification of companion candidates, while Vigan et al. (2021) presents the statistical analysis of the frequency of substellar companions and its dependence on stellar mass.

We exploited a variety of methods (kinematics and membership to groups, isochrone, lithium, rotation, and activity) to infer the stellar age and other stellar parameters. The median age value is 45 Myr, with 90% limits of 11 and 450 Myr. The median stellar mass is  $1.15 M_{\odot}$ , with 90% limits of  $0.57$  and  $2.37 M_{\odot}$ . A comparison with GPIES early statistical analysis (Nielsen et al. 2019) shows no large systematic differences in the age scales between the two studies, but significant differences in the mass distribution and binary properties.

**Acknowledgements.** SPHERE is an instrument designed and built by a consortium consisting of IPAG (Grenoble, France), MPIA (Heidelberg, Germany), LAM (Marseille, France), LESIA (Paris, France), Laboratoire Lagrange (Nice, France), INAF – Osservatorio di Padova (Italy), Observatoire de Genève (Switzerland), ETH Zürich (Switzerland), NOVA (Netherlands), ONERA (France) and ASTRON (Netherlands) in collaboration with ESO. SPHERE was funded by ESO, with additional contributions from CNRS (France), MPIA (Germany), INAF (Italy), FINES (Switzerland) and NOVA (Netherlands). SPHERE also received funding from the European Commission Sixth and Seventh Framework Programmes as part of the Optical Infrared Coordination Network for Astronomy (OPTICON) under grant number RII3-Ct-2004-001566 for FP6

(2004–2008), grant number 226 604 for FP7 (2009–2012) and grant number 312430 for FP7 (2013–2016). This research has made use of the SIMBAD database and VizieR services, operated at CDS, Strasbourg, France and of the Washington Double Star Catalog maintained at the US Naval Observatory. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. This paper includes data collected with the TESS mission, obtained from the MAST data archive at the Space Telescope Science Institute (STScI). Funding for the TESS mission is provided by the NASA Explorer Program. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5–26555. This paper has made use of data products available in ESO archive. Program ID: 60.A-9036(A); 072.C-0488(E) (PI Mayor), 074.C-0364(A) (PI Robichon), 074.C-0037(A) (PI Gunther), 075.C-0202(A) (PI Gunther), 075.C-0689(A) (PI Galland), 076.C-0010(A) (PI Gunther), 077.C-0012(A) (PI Gunther), 077.C-0295(D) (PI Galland), 078.D-0245(C) (PI Dall), 079.C-0046(A) (PI Gunther), 080.D-0151(A) (PI Hatzes), 080.C-0712(A) (PI Desort), 180.C-0886(A) (PI Bonfils), 082.C-0718(B) (PI Bonfils), 082.C-0427(A) (PI Doellinger), 082.C-0390(A) (PI Weise), 183.C-0437(A) (PI Bonfils), 083.C-0794(A) (PI Chauvin), 084.C-1039(A) (PI Chauvin), 184.C-0815(B) (PI Desort), 089.C-0732(A) (PI Lo Curto), 191.C-0873(D) (PI Bonfils), 192.C-0224(A) (PI Lagrange), 097.C-0864(B) (PI Lannier), 098.C-0739(A) (PI Lagrange), 099.C-0205(A) (PI Lagrange), 099.C-0458(A) (PI Lo Curto), 1101.C-0557(A) (PI Lagrange). We have used data from the WASP public archive in this research. The WASP consortium comprises of the University of Cambridge, Keele University, University of Leicester, The Open University, The Queen's University Belfast, St. Andrews University and the Isaac Newton Group. Funding for WASP comes from the consortium universities and from the UK's Science and Technology Facilities Council. Based on data retrieved from the SOPHIE archive at Observatoire de Haute-Provence (OHP), available at <http://atlas.obs-hp.fr/sophie/>. We thank the anonymous referee for useful comments. S.D., V.D., D.M. and R.G. acknowledge the support by INAF/Frontiera through the “Progetti Premiali” funding scheme of the Italian Ministry of Education, University, and Research, the PRIN-INAF 2019 “Planetary systems at young ages” (PLATEA) and the ASI-INAF agreement n.2018-16-HH.0. AV acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 757561). A.M.L. acknowledges funding from Agence Nationale de la Recherche (France) under contract number ANR-14-CE33-0018. J.C. was supported by SC Space Grant and Fulbright Colombia. M.B. acknowledges funding by the UK Science and Technology Facilities Council (STFC) grant no. ST/M001229/1.

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