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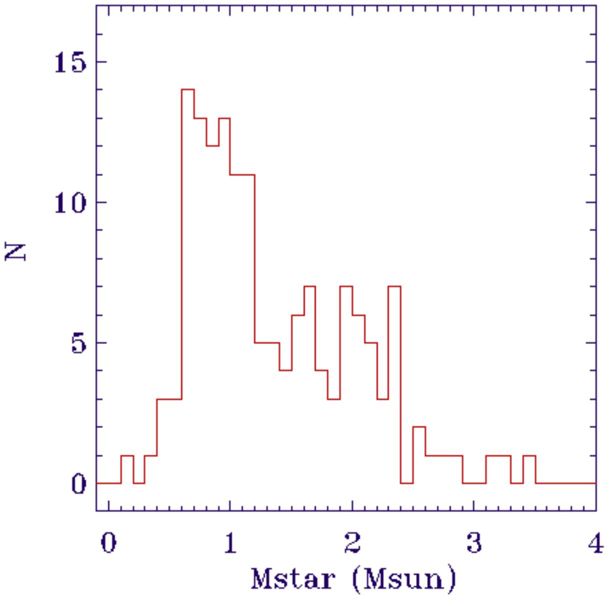

Fig. 2. Histogram of stellar masses for the F150 sample.

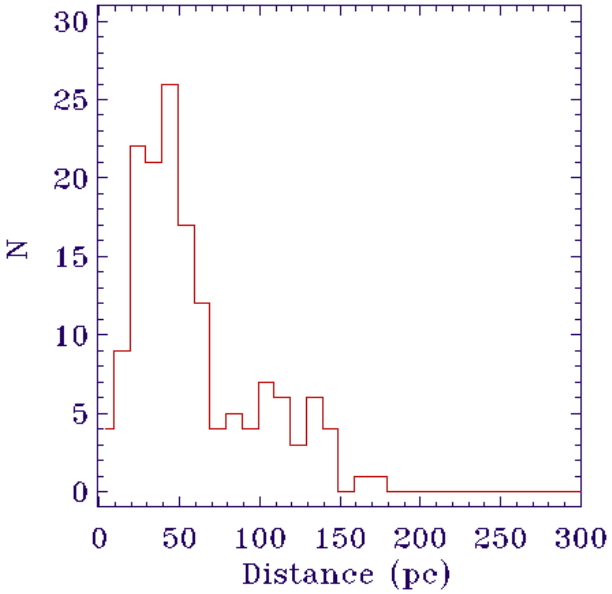

Fig. 3. Histogram of distances for the F150 sample.

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

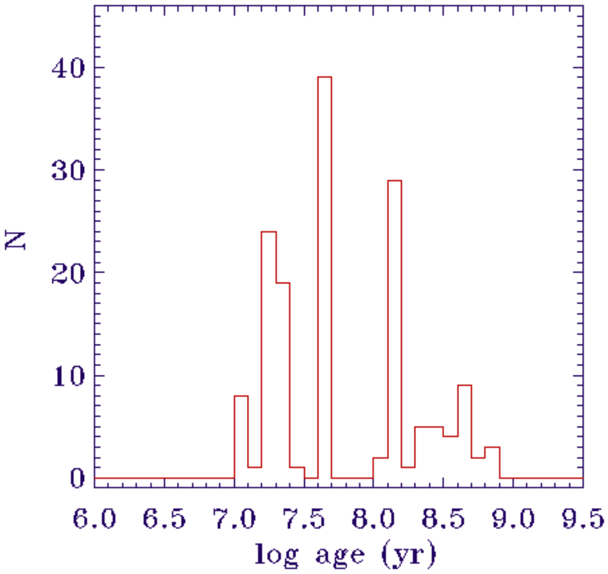

Fig. 4. Histogram of stellar ages for the F150 sample.

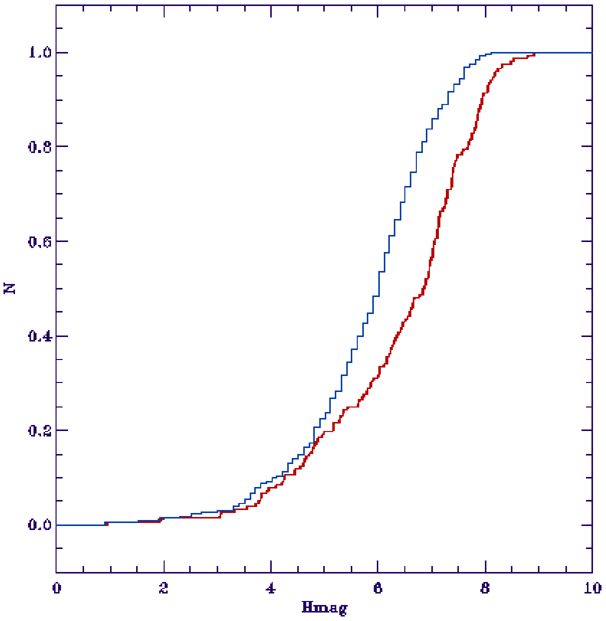

Fig. 5. Cumulative distribution of H-band magnitude for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).

The 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

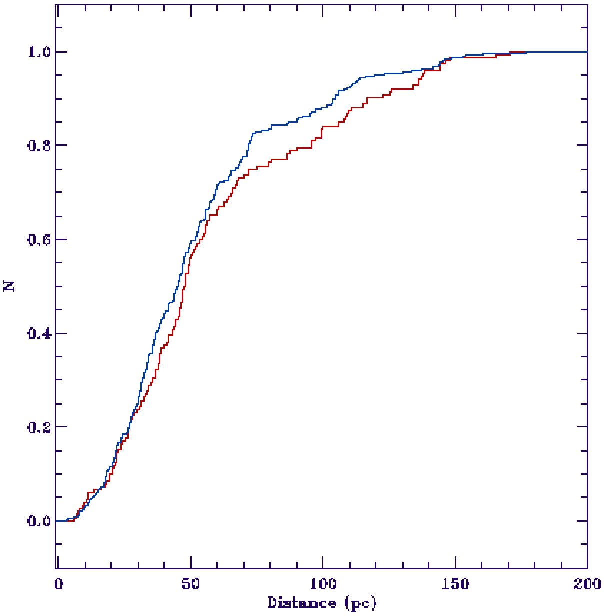

Fig. 6. Cumulative distribution of distance for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).

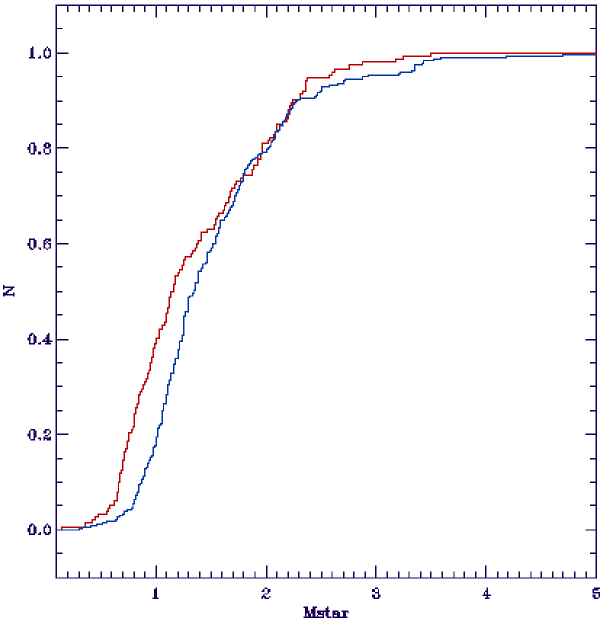

Fig. 7. Cumulative distribution of masses for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).

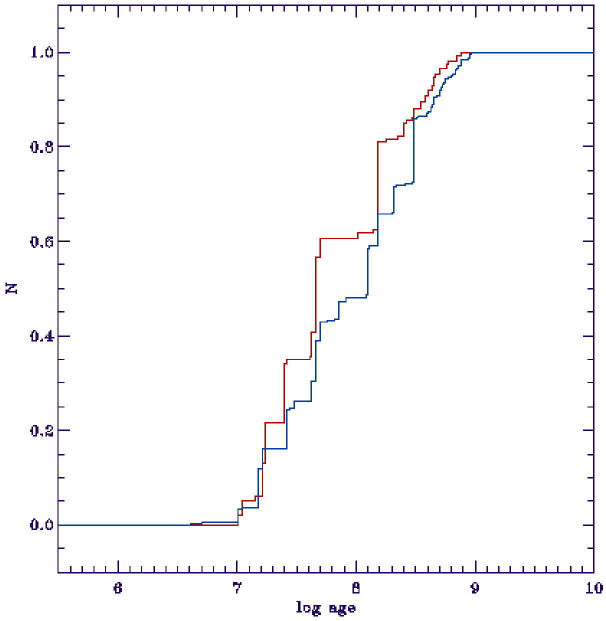

Fig. 8. Cumulative distribution of log (age) for the stars in our sample (red line) and that of Nielsen et al. (2019) (blue line).

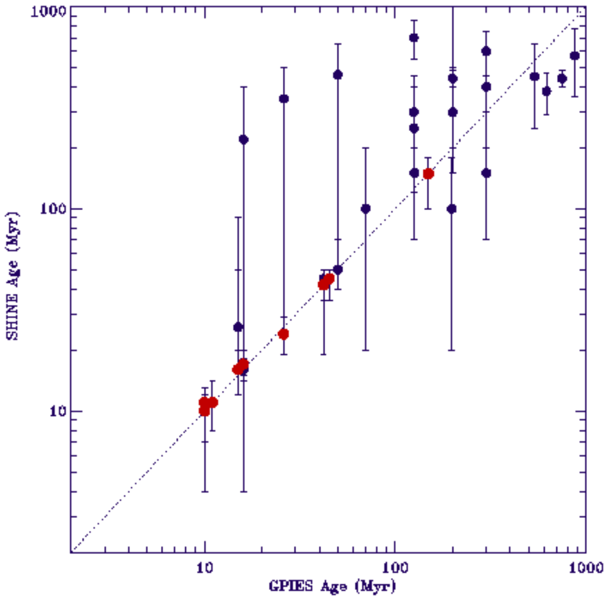

Fig. 9. Comparison of ages derived in the present work and in Nielsen et al. (2019). Black circles refer to individual stars and red circles to moving groups (typically several targets for each group). The error bars refer to the minimum and maximum age values from Table 9.

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,

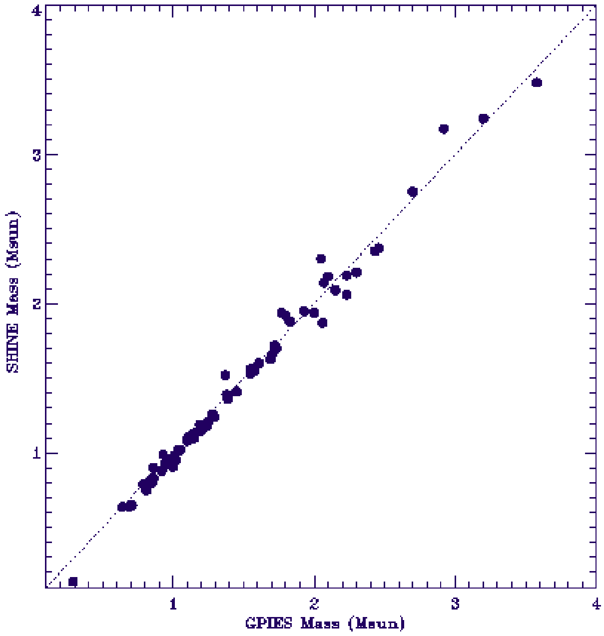

Fig. 10. Comparison of stellar masses derived in the present work and in Nielsen et al. (2019).

for which the adopted individual age is equal (TW Hya, η Cha, Tuc-Hor, Columba, Carina, Argus, AB Dor MG) or differ by a very small amount, 1 or 2 Myr (β 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-IRDIS 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.

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References

Abt, H. A. 1988, ApJ, 331, 922
Allen, C., Poveda, A., & Herrera, M. A. 2000, A&A, 356, 529
Asensio-Torres, R., Janson, M., Bonavita, M., et al. 2018, A&A, 619, A43
Baraffe, I., Chabrier, G., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701
Baraffe, I., Homeier, D., Allard, F., & Chabrier, G. 2015, A&A, 577, A42
Baratella, M., D'Orazi, V., Carraro, G., et al. 2020, A&A, 634, A34
Barbato, D., Sozzetti, A., Desidera, S., et al. 2018, A&A, 615, A175
Barenfeld, S. A., Bubar, E. J., Mamajek, E. E., & Young, P. A. 2013, ApJ, 766, 6
Barnes, J. R. 2005, MNRAS, 364, 137
Barnes, S. A. 2007, ApJ, 669, 1167
Barrado y Navascues, D. 1998, A&A, 339, 831
Bell, C. P. M., Mamajek, E. E., & Naylor, T. 2015, MNRAS, 454, 593
Beuzit, J. L., Vigan, A., Mouillet, D., et al. 2019, A&A, 631, A155
Biazzo, K., D'Orazi, V., Desidera, S., et al. 2012, MNRAS, 427, 2905
Biller, B. A., Close, L. M., Masciadri, E., et al. 2007, ApJS, 173, 143
Biller, B. A., Liu, M. C., Wahhaj, Z., et al. 2010, ApJ, 720, L82
Biller, B. A., Liu, M. C., Wahhaj, Z., et al. 2013, ApJ, 777, 160
Boccaletti, A., Thalmann, C., Lagrange, A.-M., et al. 2015, Nature, 526, 230
Boccaletti, A., Sezestre, E., Lagrange, A.-M., et al. 2018, A&A, 614, A52
Boccaletti, A., Thébault, P., Pawellek, N., et al. 2019, A&A, 625, A21
Bonavita, M. 2020, Exo-DMC: Exoplanet Detection Map Calculator
Bonavita, M., Chauvin, G., Desidera, S., et al. 2012, A&A, 537, A67
Bonavita, M., de Mooij, E. J. W., & Jayawardhana, R. 2013, PASP, 125, 849
Bonavita, M., Desidera, S., Thalmann, C., et al. 2016, A&A, 593, A38
Bonavita, M., D'Orazi, V., Mesa, D., et al. 2017, A&A, 608, A106
Bonavita, M., Gratton, R., Desidera, S., et al. 2021, A&A, submitted [arXiv:`2103.13706`]
Bonfils, X., Delfosse, X., Udry, S., et al. 2013, A&A, 549, A109
Bonnefoy, M., Chauvin, G., Lagrange, A. M., et al. 2014, A&A, 562, A127
Bonnefoy, M., Zurlo, A., Baudino, J. L., et al. 2016, A&A, 587, A58
Bonnefoy, M., Perraut, K., Lagrange, A. M., et al. 2018, A&A, 618, A63
Booth, M., Kennedy, G., Sibthorpe, B., et al. 2013, MNRAS, 428, 1263
Borgniet, S., Lagrange, A.-M., Meunier, N., et al. 2019, A&A, 621, A87
Bowler, B. P. 2016, PASP, 128, 102001
Brandt, T. D., McElwain, M. W., Turner, E. L., et al. 2014, ApJ, 794, 159
Brems, S. S., Kürster, M., Trifonov, T., Reffert, S., & Quirrenbach, A. 2019, A&A, 632, A37
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Bryan, M. L., Knutson, H. A., Lee, E. J., et al. 2019, AJ, 157, 52
Busko, I. C., & Torres, C. A. O. 1978, A&A, 64, 153
Caballero, J. A. 2009, A&A, 507, 251
Caballero, J. A. 2010, A&A, 514, A98
Cantat-Gaudin, T., & Anders, F. 2020, A&A, 633, A99
Carleo, I., Benatti, S., Lanza, A. F., et al. 2018, A&A, 613, A50
Carleo, I., Malavolta, L., Lanza, A. F., et al. 2020, A&A, 638, A5
Carson, J., Thalmann, C., Janson, M., et al. 2013, ApJ, 763, L32
Casagrande, L., Ramírez, I., Meléndez, J., Bessell, M., & Asplund, M. 2010, A&A, 512, A54
Cassan, A., Kubas, D., Beaulieu, J. P., et al. 2012, Nature, 481, 167
Chauvin, G. 2018, Proc. SPIE, 10703, 1070305
Chauvin, G., Lagrange, A. M., Dumas, C., et al. 2004, A&A, 425, L29
Chauvin, G., Lagrange, A. M., Lacombe, F., et al. 2005a, A&A, 430, 1027
Chauvin, G., Lagrange, A. M., Zuckerman, B., et al. 2005b, A&A, 438, L29
Chauvin, G., Lagrange, A. M., Bonavita, M., et al. 2010, A&A, 509, A52
Chauvin, G., Vigan, A., Bonnefoy, M., et al. 2015, A&A, 573, A127
Chauvin, G., Desidera, S., Lagrange, A. M., et al. 2017a, in SF2A-2017: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, ed. C. Reylé, P. Di Matteo, F. Herpin, E. Lagadec, A. Lançon, Z. Meliani, & F. Royer, Di
Chauvin, G., Desidera, S., Lagrange, A.-M., et al. 2017b, A&A, 605, L9
Chauvin, G., Gratton, R., Bonnefoy, M., et al. 2018, A&A, 617, A76
Cheetham, A., Bonnefoy, M., Desidera, S., et al. 2018, A&A, 615, A160
Cheetham, A. C., Samland, M., Brems, S. S., et al. 2019, A&A, 622, A80
Chen, C. H., Mittal, T., Kuchner, M., et al. 2014a, ApJS, 211, 25
Chen, Y., Girardi, L., Bressan, A., et al. 2014b, MNRAS, 444, 2525
Chilcote, J., Pueyo, L., De Rosa, R. J., et al. 2017, AJ, 153, 182
Choquet, É., Perrin, M. D., Chen, C. H., et al. 2016, ApJ, 817, L2
Chugainov, P. F. 1974, Izvestiya Ordena Trudovogo Krasnogo Znameni Krymskoj Astrofizicheskoj Observatorii, 52, 3
Claudi, R. U., Turatto, M., Gratton, R. G., et al. 2008, Proc. SPIE, 7014, 70143E
Cumming, A., Butler, R. P., Marcy, G. W., et al. 2008, PASP, 120, 531
Currie, T., Lisse, C. M., Kuchner, M., et al. 2015, ApJ, 807, L7
Cutispoto, G., Pastori, L., Tagliaferri, G., Messina, S., & Pallavicini, R. 1999, A&AS, 138, 87
Damiani, F., Prisinzano, L., Pillitteri, I., Micela, G., & Sciortino, S. 2019, A&A, 623, A112
David, T. J., & Hillenbrand, L. A. 2015, ApJ, 804, 146
Delorme, P., Schmidt, T., Bonnefoy, M., et al. 2017, A&A, 608, A79
De Rosa, R. J., Rameau, J., Patience, J., et al. 2016, ApJ, 824, 121
De Rosa, R. J., Esposito, T. M., Hirsch, L. A., et al. 2019, AJ, 158, 225
De Rosa, R. J., Nielsen, E. L., Wang, J. J., et al. 2020, AJ, 159, 1
Desidera, S., Covino, E., Messina, S., et al. 2011, A&A, 529, A54
Desidera, S., Covino, E., Messina, S., et al. 2015, A&A, 573, A126
de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354
Dohlen, K., Langlois, M., Saisse, M., et al. 2008, Proc. SPIE, 7014, 70143L
Elliott, P., Bayo, A., Melo, C. H. F., et al. 2014, A&A, 568, A26
Engler, N., Boccaletti, A., Schmid, H. M., et al. 2019, A&A, 622, A192
Engler, N., Lazzoni, C., Gratton, R., et al. 2020, A&A, 635, A19
Esposito, S., Mesa, D., Skemer, A., et al. 2013, A&A, 549, A52
Fernandes, R. B., Mulders, G. D., Pascucci, I., Mordasini, C., & Emsenhuber, A. 2019, ApJ, 874, 81
Frasca, A., Guillout, P., Klutsch, A., et al. 2018, A&A, 612, A96
Gagné, J., Mamajek, E. E., Malo, L., et al. 2018a, ApJ, 856, 23
Gagné, J., Roy-Loubier, O., Faherty, J. K., Doyon, R., & Malo, L. 2018b, ApJ, 860, 43
Gaia Collaboration (Brown, A. G. A., et al.) 2016, A&A, 595, A2
Gaia Collaboration (Brown, A. G. A., et al.) 2018, A&A, 616, A1
Galicher, R., Marois, C., Macintosh, B., et al. 2016, A&A, 594, A63
Goldman, B., Röser, S., Schilbach, E., Moór, A. C., & Henning, T. 2018, ApJ, 868, 32
Grandjean, A., Lagrange, A. M., Beust, H., et al. 2019, A&A, 627, L9
Grandjean, A., Lagrange, A. M., Keppler, M., et al. 2020, A&A, 633, A44
Greenbaum, A. Z., Pueyo, L., Ruffio, J.-B., et al. 2018, AJ, 155, 226
Guenther, E. W., Neuhäuser, R., Huélamo, N., Brandner, W., & Alves, J. 2001, A&A, 365, 514
Haffert, S. Y., Bohn, A. J., de Boer, J., et al. 2019, Nat. Astron., 3, 749

Heinze, A. N., Hinz, P. M., Kenworthy, M., et al. 2010, ApJ, 714, 1570
Herbst, W., Bailer-Jones, C. A. L., Mundt, R., Meisenheimer, K., & Wackermann, R. 2002, A&A, 396, 513
Hines, D. C., Schneider, G., Hollenbach, D., et al. 2007, ApJ, 671, L165
Hinkley, S., Kraus, A. L., Ireland, M. J., et al. 2015, ApJ, 806, L9
Hormuth, F., Hippler, S., Brandner, W., Wagner, K., & Henning, T. 2008, Proc. SPIE, 7014, 701448
Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Howard, A. W., Marcy, G. W., Johnson, J. A., et al. 2010, Science, 330, 653
Hünsch, M., Schmitt, J. H. M. M., Sterzik, M. F., & Voges, W. 1999, A&AS, 135, 319
Ingraham, P., Marley, M. S., Saumon, D., et al. 2014, ApJ, 794, L15
Janson, M., Carson, J. C., Lafrenière, D., et al. 2012, ApJ, 747, 116
Janson, M., Asensio-Torres, R., André, D., et al. 2019, A&A, 626, A99
Johnson, D. R. H., & Soderblom, D. R. 1987, AJ, 93, 864
Johnson, J. A., Aller, K. M., Howard, A. W., & Crepp, J. R. 2010, PASP, 122, 905
Kalas, P., Fitzgerald, M. P., & Graham, J. R. 2007, ApJ, 661, L85
Kalas, P., Graham, J. R., Chiang, E., et al. 2008, Science, 322, 1345
Keppler, M., Benisty, M., Müller, A., et al. 2018, A&A, 617, A44
King, J. R., Villarreal, A. R., Soderblom, D. R., Gulliver, A. F., & Adelman, S. J. 2003, AJ, 125, 1980
Kiraga, M. 2012, Acta Astron., 62, 67
Koen, C., & Eyer, L. 2002, MNRAS, 331, 45
Kraus, A. L., Shkolnik, E. L., Allers, K. N., & Liu, M. C. 2014, AJ, 147, 146
Kunder, A., Kordopatis, G., Steinmetz, M., et al. 2017, AJ, 153, 75
Kuzuhara, M., Tamura, M., Kudo, T., et al. 2013, ApJ, 774, 11
Lafrenière, D., Doyon, R., Marois, C., et al. 2007, ApJ, 670, 1367
Lafrenière, D., Jayawardhana, R., & van Kerkwijk, M. H. 2008, ApJ, 689, L153
Lafrenière, D., Jayawardhana, R., Janson, M., et al. 2011, ApJ, 730, 42
Lagrange, A.-M., Desort, M., Galland, F., Udry, S., & Mayor, M. 2009, A&A, 495, 335
Lagrange, A.-M., Rubini, P., Brauner-Vettier, N., et al. 2016, Proc. SPIE, 9910, 991033
Lagrange, A. M., Boccaletti, A., Langlois, M., et al. 2019, A&A, 621, L8
Lamm, M. H., Bailer-Jones, C. A. L., Mundt, R., Herbst, W., & Scholz, A. 2004, A&A, 417, 557
Langlois, M., Gratton, R., Lagrange, A. M., et al. 2021, A&A, 651, A71
Lawler, S. M., Greenstreet, S., & Gladman, B. 2015, ApJ, 802, L20
Lawson, W. A., & Crause, L. A. 2005, MNRAS, 357, 1399
Lee, J., & Song, I. 2019, MNRAS, 489, 2189
Liu, M. C. 2004, Science, 305, 1442
Lowrance, P. J., Schneider, G., Kirkpatrick, J. D., et al. 2000, ApJ, 541, 390
Luhman, K. L., Wilson, J. C., Brandner, W., et al. 2006, ApJ, 649, 894
Macintosh, B., Graham, J. R., Ingraham, P., et al. 2014, Proceedings of the National Academy of Science, 111, 12661
Macintosh, B., Graham, J. R., Barman, T., et al. 2015, Science, 350, 64
Madsen, S., Dravins, D., & Lindegren, L. 2002, A&A, 381, 446
Maire, A.-L., Bonnefoy, M., Ginski, C., et al. 2016, A&A, 587, A56
Maire, A. L., Rodet, L., Lazzoni, C., et al. 2018, A&A, 615, A177
Maire, A. L., Rodet, L., Cantalloube, F., et al. 2019, A&A, 624, A118
Malo, L., Doyon, R., Lafrenière, D., et al. 2013, ApJ, 762, 88
Mamajek, E. E. 2012, ApJ, 754, L20
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Mamajek, E. E., Lawson, W. A., & Feigelson, E. D. 1999, ApJ, 516, L77
Marley, M. S., Fortney, J. J., Hubickyj, O., Bodenheimer, P., & Lissauer, J. J. 2007, ApJ, 655, 541
Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., & Nadeau, D. 2006, ApJ, 641, 556
Marois, C., Macintosh, B., Barman, T., et al. 2008, Science, 322, 1348
Marois, C., Zuckerman, B., Konopacky, Q. M., Macintosh, B., & Barman, T. 2010, Nature, 468, 1080
Marsden, S. C., Jardine, M. M., Ramírez Vélez, J. C., et al. 2011, MNRAS, 413, 1939
Mawet, D., Pueyo, L., Lawson, P., et al. 2012, Proc. SPIE, 8442, 844204
Mayor, M., Marmier, M., Lovis, C., et al. 2011, ArXiv e-prints, [arXiv:`1109.2497`]
Mesa, D., Gratton, R., Zurlo, A., et al. 2015, A&A, 576, A121
Mesa, D., Keppler, M., Cantalloube, F., et al. 2019, A&A, 632, A25
Messina, S., Rodonò, M., & Guinan, E. F. 2001, A&A, 366, 215
Messina, S., Desidera, S., Turatto, M., Lanzafame, A. C., & Guinan, E. F. 2010, A&A, 520, A15
Messina, S., Desidera, S., Lanzafame, A. C., Turatto, M., & Guinan, E. F. 2011, A&A, 532, A10
Messina, S., Millward, M., Buccino, A., et al. 2017, A&A, 600, A83
Meyer, M. R., Amara, A., Reggiani, M., & Quanz, S. P. 2018, A&A, 612, L3
Milli, J., Vigan, A., Mouillet, D., et al. 2017, A&A, 599, A108
Milli, J., Engler, N., Schmid, H. M., et al. 2019, A&A, 626, A54
Miret-Roig, N., Galli, P. A. B., Brandner, W., et al. 2020, A&A, 642, A179
Moerchen, M. M., Telesco, C. M., Packham, C., & Kehoe, T. J. J. 2007, ApJ, 655, L109
Moerchen, M. M., Telesco, C. M., & Packham, C. 2010, ApJ, 723, 1418
Montes, D., López-Santiago, J., Gálvez, M. C., et al. 2001, MNRAS, 328, 45
Montesinos, B., Eiroa, C., Krivov, A. V., et al. 2016, A&A, 593, A51
Mouillet, D., Beuzit, J. L., Desidera, S., et al. 2010, in In the Spirit of Lyot 2010, E50
Moultaka, J., Ilovaisky, S. A., Prugniel, P., & Soubiran, C. 2004, PASP, 116, 693
Mugrauer, M., Vogt, N., Neuhäuser, R., & Schmidt, T. O. B. 2010, A&A, 523, L1
Müller, A., Keppler, M., Henning, T., et al. 2018, A&A, 617, L2
Nakajima, T., & Morino, J.-I. 2012, AJ, 143, 2
Neuhäuser, R., Guenther, E. W., Wuchterl, G., et al. 2005, A&A, 435, L13
Nielsen, E. L., Liu, M. C., Wahhaj, Z., et al. 2013, ApJ, 776, 4
Nielsen, E. L., De Rosa, R. J., Macintosh, B., et al. 2019, AJ, 158, 13
Oelkers, R. J., Rodriguez, J. E., Stassun, K. G., et al. 2018, AJ, 155, 39
Olofsson, J., Samland, M., Avenhaus, H., et al. 2016, A&A, 591, A108
Olofsson, J., van Holstein, R. G., Boccaletti, A., et al. 2018, A&A, 617, A109
Pecaut, M. J., & Mamajek, E. E. 2013, ApJS, 208, 9
Pecaut, M. J., & Mamajek, E. E. 2016, MNRAS, 461, 794
Pecaut, M. J., Mamajek, E. E., & Bubar, E. J. 2012, ApJ, 746, 154
Perrot, C., Thebault, P., Lagrange, A.-M., et al. 2019, A&A, 626, A95
Plavchan, P., Barclay, T., Gagné, J., et al. 2020, Nature, 582, 497
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 2002, Numerical Recipes in C++ : The Art of Scientific Computing (Cambridge University Press)
Rajan, A., Rameau, J., De Rosa, R. J., et al. 2017, AJ, 154, 10
Rameau, J., Chauvin, G., Lagrange, A.-M., et al. 2013a, ApJ, 772, L15
Rameau, J., Chauvin, G., Lagrange, A. M., et al. 2013b, A&A, 553, A60
Rameau, J., Nielsen, E. L., De Rosa, R. J., et al. 2016, ApJ, 822, L29
Rebull, L. M., Stapelfeldt, K. R., Werner, M. W., et al. 2008, ApJ, 681, 1484
Rebull, L. M., Stauffer, J. R., Bouvier, J., et al. 2016, AJ, 152, 113
Reddy, A. B. S., & Lambert, D. L. 2017, ApJ, 845, 151
Reffert, S., Bergmann, C., Quirrenbach, A., Trifonov, T., & Künstler, A. 2013, in Protostars and Planets VI Posters, 28
Reid, I. N., Gizis, J. E., & Hawley, S. L. 2002, AJ, 124, 2721
Rizzuto, A. C., Ireland, M. J., & Robertson, J. G. 2011, MNRAS, 416, 3108
Roberts, D. H., Lehar, J., & Dreher, J. W. 1987, AJ, 93, 968
Robin, A., & Creze, M. 1986, A&A, 157, 71
Rodet, L., Bonnefoy, M., Durkan, S., et al. 2018, A&A, 618, A23
Rodriguez, D. R., Duchêne, G., Tom, H., et al. 2015, MNRAS, 449, 3160
Samland, M., Mollière, P., Bonnefoy, M., et al. 2017, A&A, 603, A57
Scargle, J. D. 1982, ApJ, 263, 835
Schneider, G., Smith, B. A., Becklin, E. E., et al. 1999, ApJ, 513, L127
Schneider, A. C., Shkolnik, E. L., Allers, K. N., et al. 2019, AJ, 157, 234
Sissa, E., Gratton, R., Garufi, A., et al. 2018, A&A, 619, A160
Smith, L. C., Lucas, P. W., Contreras Peña, C., et al. 2015, MNRAS, 454, 4476
Soummer, R., Perrin, M. D., Pueyo, L., et al. 2014, ApJ, 786, L23
Spina, L., Nordlander, T., Casey, A. R., et al. 2020, ApJ, 895, 52
Stauffer, J., Rebull, L. M., Cody, A. M., et al. 2018, AJ, 156, 275
Su, K. Y. L., Rieke, G. H., Stansberry, J. A., et al. 2006, ApJ, 653, 675
Sumi, T., Kamiya, K., Bennett, D. P., et al. 2011, Nature, 473, 349
Tanner, A., Plavchan, P., Bryden, G., et al. 2020, PASP, 132, 084401
Tokovinin, A. 2008, MNRAS, 389, 925
Torres, C. A. O., Quast, G. R., da Silva, L., et al. 2006, A&A, 460, 695
Torres, C. A. O., Quast, G. R., Melo, C. H. F., & Sterzik, M. F. 2008, in Handbook of Star Forming Regions, II, ed. Reipurth, B., 757
Tuthill, P., Lloyd, J., Ireland, M., et al. 2006, Proc. SPIE, 6272, 62723A
van Leeuwen, F. 2007, A&A, 474, 653
Viana Almeida, P., Santos, N. C., Melo, C., et al. 2009, A&A, 501, 965
Vican, L. 2012, AJ, 143, 135
Vigan, A., Moutou, C., Langlois, M., et al. 2010, MNRAS, 407, 71
Vigan, A., Patience, J., Marois, C., et al. 2012, A&A, 544, A9
Vigan, A., Bonavita, M., Biller, B., et al. 2017, A&A, 603, A3
Vigan, A., Fontanive, C., Meyer, M., et al. 2021, A&A, 651, A72
Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
Voges, W., Aschenbach, B., Boller, T., et al. 2000, IAU Circ., 7432, 3
Wahhaj, Z., Liu, M. C., Biller, B. A., et al. 2011, ApJ, 729, 139
Wahhaj, Z., Liu, M. C., Nielsen, E. L., et al. 2013, ApJ, 773, 179
Wang, S., Liu, J., Qiu, Y., et al. 2016, ApJS, 224, 40
Wang, J. J., Graham, J. R., Dawson, R., et al. 2018, AJ, 156, 192
Wright, N. J., & Mamajek, E. E. 2018, MNRAS, 476, 381
Wright, J. T., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2004, ApJS, 152, 261
Wright, N. J., Drake, J. J., Mamajek, E. E., & Henry, G. W. 2011, ApJ, 743, 48
Zuckerman, B. 2019, ApJ, 870, 27