Scientific Justification:

Throughout their lifetimes and especially at the ends of their lives, massive stars are by far the largest contributor of processed material to the interstellar medium — material which is later recycled into second- and third-generation stars, terrestrial planets, and SIM investigators. A typical O star may eject matter at the rate of 10^{-6} to 10^{-5} $M_\odot$ per year, relinquishing an appreciable fraction of its total mass during its short lifetime. Much of the remaining material is then distributed during the star's final evolutionary phases, as ejected shells and supernova remnant.

Much of the detail as to the amount of material dispersed by massive stars is unknown, however, largely due to our poor knowledge of these objects' masses. While a "good" mass determination for a solar-type star is now approaching the 1% level and better, a "good" mass determination for an O star is perhaps 30% or more. Those with small quoted errors are typically eclipsing systems with periods so short they have likely not been fully detached during their lifetimes, making results not directly applicable to single stars.

Several factors conspire to make mass determinations of these objects difficult:

- High surface temperatures and rapid rotation result in broad spectral lines, limiting the accuracy of radial velocity determinations for spectroscopic pairs; interaction between components due to stellar winds further complicates the picture.
- O stars make up a small fraction of the stellar population, giving us fewer suitable targets for study. Those available are on average much further from us, so distances are less reliable. See discussion of parallax errors below.
- O stars have very high multiplicity rates, and many components are probably not yet discovered. These unknown pairs can exacerbate any difficulties in determining absolute magnitude even when the parallax is adequately known.
- Finally, most O stars are found in associations, so parallax determinations for even the closer objects are frequently complicated by crowded fields, to say nothing of the often extreme amounts of nebulosity surrounding them.

For one subset of O stars, however — the runaway stars — some of these complications are reduced, allowing us the possibility of determining reliable distances for a variety of luminosities and spectral types. The resulting improved calibration of O-star spectroscopic distances could in turn improve our mass estimates for these important contributors to the ISM. This proposal aims to increase the known sample of massive (O, early B, WR) runaway stars and to provide a list of suitable targets for parallax determination by SIM.

Runaway stars (see Blaauw 1961) are massive stars which have been ejected from their associations, through one of at least two possible mechanisms (see Leonard 1990). A close encounter between two binary systems in the association may result in the disruption of both systems, with one or more of the stars being ejected at high velocities. Alternatively, a supernova explosion by one component of a binary or multiple system may result in the remaining component(s) being similarly ejected. The most well-known example is the system comprised of AE Aur, 53 Ari, and μ Col, two of which are shown in Figure 1 (from Hoogerwerf et al. 2000). Motions of all three stars can be traced back to the same nebula, the site of an earlier supernova which presumably caused their ejection.

Runaways as Parallax Targets

The suitability of runaways for possible parallax determination lies in two factors. First, their ejection from their original nebulosity may place the objects in a less-crowded field. Perhaps more importantly, the ejection process virtually guarantees that the objects are either single stars or extremely hard spectroscopic binaries. These spectroscopic pairs should be easily discernable, allowing us to produce a clean sample of single massive stars for distance determination.

In the recent *Galactic O Star Catalog* of Maíz–Apellániz et al. (2004), 24 stars, or approximately 6% of the 378 catalogued objects, were classified as tentative runaway stars. (The runaway status of another 35 field stars was listed as “no:”, indicating uncertain status). An additional source of these objects may be found in the *Seventh Catalogue of Galactic Wolf-Rayet Stars* and its more recent *Annex* (van der Hucht 2001, 2006), which list 206 WR stars brighter than $V = 18$. If the percentage of runaways found by Maíz–Apellániz et al. for O stars holds for these objects as well, the van der Hucht catalogs could potentially yield ∼10-15 runaway targets for parallax determination, in addition to the 24 O-star runaways.

We also believe that the current sample of runaway stars significantly underestimates the true total, simply due to the lack of available proper motion and radial velocity data. A major improvement to our knowledge of proper motions is soon to become available, however, due to the upcoming release of the *Third USNO CCD Astrograph Catalog* (UCAC3), scheduled for the end of this year. UCAC3 will provide positions and proper motions for over 50 million stars down to a magnitude of 16, with positional accuracies of roughly 20 mas for $10 < V < 14$ and 70 mas at $V = 16$. Proper motion accuracies of 2–6 mas/year are expected for stars in the magnitude range of interest. As contributors to the UCAC3 project, we will have access to the project’s results (and to the expertise of its authors) prior to the official data release. With these new data we could potentially double the current runaway total, even assuming a rather modest increase in our success rate (see discussion in Technical Approach section below).

We propose, then, to substantially increase the sample of known runaway stars (and confirm the status of stars on the current tentative "yes" and "no:" lists), using new proper motions from the upcoming UCAC3 catalog as well as radial velocities from the literature to analyze all known O and Wolf-Rayet stars. This sample will form the basis for a list of SIM targets aimed at improving the distances of Galactic O and WR stars, calibrating the spectroscopic distance scale and leading to more accurate mass estimates for these massive stars.

Improving O-star Parallaxes — why SIM?

Figure 2 compares the quality of Hipparcos O-star parallax determinations with those of other stars in the Hipparcos Catalogue. Two conclusions are obvious: first, O-star parallax values are small and relative errors are large — most are 30-50% — corresponding to mass sum errors of a factor of 2-3. Second, the number of O stars with any parallax determination at all is small; only 33 objects, or less than 10% of the objects in the Maíz–Apellániz et al. catalog, despite the fact that nearly all stars in the catalog are bright enough for Hipparcos to have observed them. (most of the remaining objects in the O star catalog have *negative* Hipparcos parallaxes, due to these objects' large distances.)

SIM has the potential to vastly improve this picture. First, its expected astrometric accuracy (currently $4.2\,\mu$as, although potentially as low as $3\,\mu$as, according to Unwin et al. 2008) is at least a 25-fold improvement in parallax error (or alternatively, distance range) over Hipparcos. Restriction of observations to the proposed "clean" runaway star list will avoid the duplicity / crowded field / nebulosity issues which plague most O-star distance determinations, further improving the quality of the final O-star parallax results.

It should also be noted that SIM will have significant advantages in accuracy over Gaia at both ends of the magnitude range. For G0V stars with no extinction, Lindegren et al. (2007) quotes expected accuracies of $8\,\mu$as for stars in the 6–13 mag range, decreasing to $34\,\mu$as at $V = 16$ and $90\,\mu$as at $V = 18$ [according to de Bruijne (2005), color effects will decrease Gaia accuracy by an additional 1-2 μas for an O star at $V = 15$]. However, $\sim$20% of are expected targets are brighter than $V = 6$; Gaia will not be able to observe these objects, as saturation issues (which affect all stars brighter than $V \sim 12$) will become too large for mitigation. Many of the stars in the WR Catalog are quite faint; for those in the $16 < V < 18$ range, SIM accuracies are 4–10 times better even if observations are not pushed to their limits. **Thus, SIM can achieve at least a factor of two increase in parallax accuracy over Gaia — and considerably more for the fainter stars in the sample — a critical improvement for calibrating these distant objects. SIM is also the only mission which can observe the brightest 20% of the sample.**

Technical Approach:

The O-star runaway study will use as it's starting point the 378 stars in the Maíz–Apellániz et al. (2004) *Galactic O Star Catalog.* The catalog will be updated with any new duplicity information obtained during our recent interferometric surveys for O-star duplicity (Turner et al. 2008, Mason et al. in preparation). Position and proper motion information for all objects will be updated, based on results from the upcoming *Third USNO CCD Astrograph Catalog* (UCAC3).

Literature searches will be undertaken for any additional radial velocity and spectral data. Motions of all objects in the catalog will then be examined, in order to (1) verify the runaway nature of the 24 objects tentatively so-designated, and (2) identify any new runaway candidates. The 35 stars whose runaway status were given as "no:" by Maíz–Apellániz et al. will be paid particular attention.

The 208 Wolf Rayet stars from the van der Hucht (2001, 2006) *VIIth catalogue of galactic Wolf-Rayet stars* and its *Annex* that are brighter than $V = 18$ will be treated in a similar manner. Position and proper motion information will be taken from UCAC3 for stars brighter than $V \sim 16$, or from the Northern and Southern Proper Motion catalogs (in combination with the USNO-B catalog) for stars in the $16 < V < 18$ range. (The faintest stars in the WR catalogs will be excluded from this project; for these objects proper motion data may be unavailable or of lower quality, and SIM observations of any determined to be possible runaways would be prohibitively time-consuming).

The eventual number of runaway O and WR stars is of course unknown at this point; however, in order to arrive at an initial estimate of the SIM mission time required for parallax determination, we assume a conservative "success rate" in order to derive a sample list. We assume that all 24 tentative O-star runaways are retained, and that perhaps 20% of the "no:" stars will be determined to be runaways following further analysis. This yields an O-star sample of 31 stars, or 8% of the Maíz–Apellániz et al. list. A similar percentage of the two van der Hucht lists would yield an additional 15–18 stars. A complete WAG list, then, might be of order 45–50 objects.

Table 1 gives the magnitude distribution of our WAG list, based on actual magnitudes of the known runaways ($2.3 < V < 8.5$), as well as the distributions in magnitude of the O-star "no:" stars ($7.6 < V < 11.2$) and the brighter WR stars ($1.7 < V < 18.0$). Also shown are the required mission time to observe each object and achieve parallax accuracies of 4.2, 5, and 8 μas. (The number of visits per object — chosen to minimize mission time — is indicated in parentheses beside each individual mission time.)

Based on this table, it appears feasible to attempt to obtain the highest possible parallax accuracy for all target objects brighter than 12 or even 14, and possibly reduce the accuracy to 5 or 8 μas for the faintest objects, depending on the number of objects actually determined to be runaway stars. Total mission time has been subtotalled for the brighter and fainter samples to better illustrate the effects of modifying parallax accuracy on overall mission time.

Finally, Table 2 illustrates the $1\,\sigma$ distance errors resulting from the above-mentioned parallax errors for an O8V star at various brightnesses (including some simplified values of interstellar extinction). Absolute magnitudes for the Wolf-Rayet stars in our sample range from about -2.2 to -7.6, while most O stars fall in the range -4.0 to -5.7; thus our O8V star at $M_{\rm V} = -4.8$ is a fairly typical value.

Gaia is unable to observe the brightest example in this table, as saturations issues will exclude all stars brighter than $V \sim 6$. For the faintest example, the Gaia parallax error is larger than the parallax itself, leading to a meaningless upper distance error.

REFERENCES

Blaauw, A. 1961, Bull. Astron. Inst. Netherlands **15**, 265

de Bruijne, J.H.J. 2005, *Accuracy Budget and Performance*, Proceedings of the Gaia Symposium *The Three-Dimensional Universe with Gaia* (ESA SP-576), p. 35

Hoogerwerf, R., de Bruijne, J.H.J., & de Zeeuw, P.T. 2000, *The Origin of Runaway Stars*, ApJ **544**, L133

Leonard, P.J.T. 1990, *On the origin of the OB runaway stars*, JRASC **84**, 216

Lindegren, L. et al. 2007, *The Gaia mission: science, organization, and present status*, IAU Symp. 248, *A Giant Step: from Milli- to Micro-arcsecond Astronomy*, W.J. Jin, I. Platais, & M.A.C. Perryman, eds., 217

Maíz–Apellániz, Walborn, N.R., Galué, H.Á., & Wei, L.H. 2004, *A Galactic O Star Catalog*, ApJSS **151**, 103

Turner, N.H., ten Brummelaar, T.A., Roberts, Jr., L.C., Mason, B.D., Hartkopf, W.I., & Gies, D.R. 2008, *Adaptive Optics Photometry and Astrometry of Binary Stars. III. A Faint Companion Search of O-Star Systems*, AJ, in press (July)

Unwin, S.C. et al. 2008, *Taking the Measure of the Universe: Precision Astrometry with SIM PlanetQuest*, PASP **120**, 38

van der Hucht, K.A. 2001, *The VIIth catalogue of galactic Wolf-Rayet stars*, NewAR **45**, 135

van der Hucht, K.A. 2006, *New Galactic Wolf-Rayet stars and candidates. An annex to The VIIth catalogue of galactic Wolf-Rayet stars*, A&A **458**, 453

This preprint was prepared with the AAS LaTeX macros v4.0.

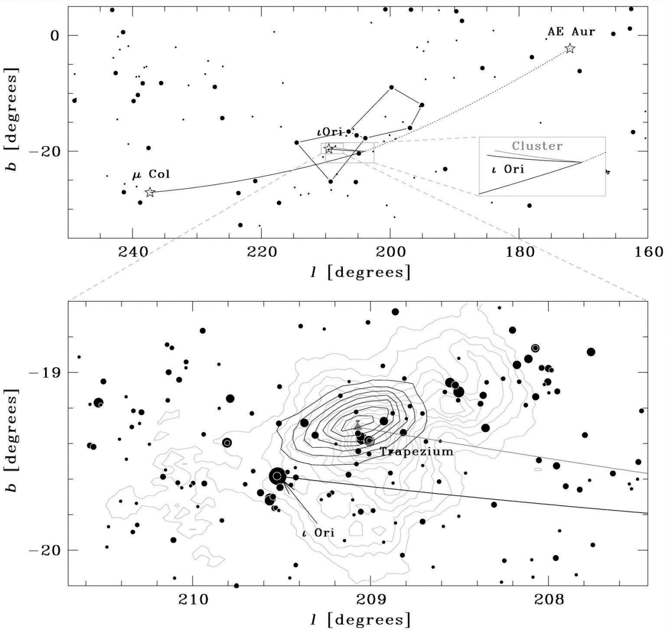

Fig. 1.— Motions of the runaway stars AU Aur and μ Col and the binary ι Ori from their present positions (shown as stars) back to the time of closest separation, roughly 2.5 Myr ago. The lower frame also illustrates motion of the Trapezium over this period. From Hoogerwerf et al. (2000).

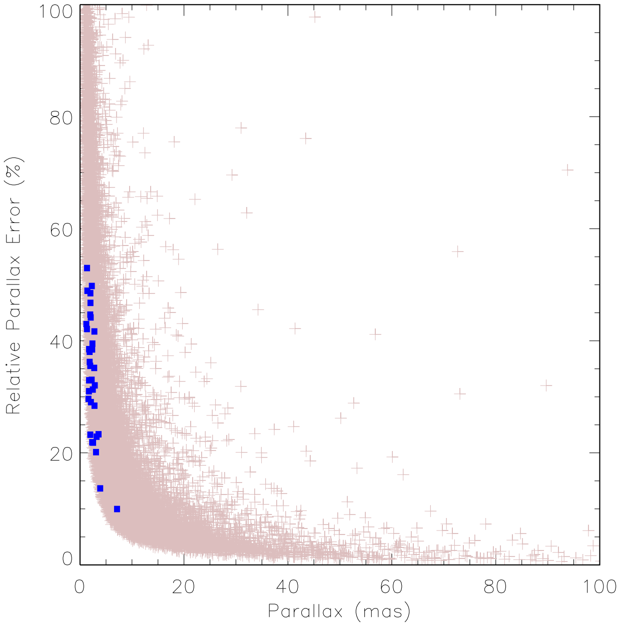

Fig. 2.— Relative Hipparcos parallax errors (percent error) versus parallax in mas. Shown are a random sample of 20% of the parallax values from the Hipparcos catalog (excluding values of π less than zero and a few very large parallax values, as well as errors greater than 100%). The handful of available positive O star parallaxes in the catalog are shown as filled blue squares.

Table 1: SIM mission time (in hours) required for the predicted sample, assuming different levels of mission parallax accuracy. The numbers of visits per object which minimize mission time are given in parentheses. All values are derived using the SIM Global Astrometry Time Estimator.

V Range	N	Mission Time per Object (hours) 4.2μas	5μas	8μas	Total Mission Time (hours) 4.2μas	5μas	8μas
2 – 6	9	0.97 (100)	0.49 (50)	0.49 (50)	8.73	4.41	4.41
6 – 9	21	0.97 (100)	0.49 (50)	0.49 (50)	20.37	10.29	10.29
9 – 10	3	1.00 (100)	0.49 (50)	0.49 (50)	3.00	1.47	1.47
10 – 11	3	1.10 (100)	0.51 (50)	0.49 (50)	3.30	1.53	1.47
11 – 12	1	1.35 (110)	0.69 (55)	0.49 (50)	1.35	0.69	0.49
Subtotal	**37**				**36.75**	**18.39**	**18.13**
12 – 13	3	1.87 (150)	0.97 (75)	0.50 (50)	5.61	2.91	1.50
13 – 14	1	2.97 (150)	1.48 (85)	0.61 (50)	2.97	1.48	0.61
14 – 15	2	5.50 (150)	2.68 (100)	0.93 (50)	11.00	5.36	1.86
15 – 16	1	11.2 (150)	5.67 (135)	1.79 (50)	11.2	5.67	1.79
16 – 17	1	26.6 (200)	13.0 (100)	3.73 (50)	26.6	13.0	3.73
17 – 18	1	76.5 (150)	33.3 (125)	10.1 (50)	76.5	33.3	10.1
Subtotal	**9**				**133.9**	**61.7**	**19.6**
Total	**46**				**170.7**	**80.0**	**37.7**

Table 2: Distance errors for Gaia and SIM as a function of magnitude, for an O8V star ($M_{\rm V}$ = -4.8). Interstellar extinction ranges from 1 to 7 magnitudes (a bit of a simplification...)

V (mag)	$A_{\rm V}$ (mag)	π (μas)	Dist. (pc)	Parallax Error (μas) Gaia	SIM	Distance Error (pc) Gaia	SIM
4	0	1738	575	—	4.2	—	+1/−1
6	1	1096	912	8	4.2	+7/−7	+4/−3
8	2	692	1445	8	4.2	+17/−17	+9/−9
10	3	436	2291	8	4.2	+43/−41	+22/−22
12	4	275	3631	8	4.2	+109/−101	+56/−55
14	5	174	5754	13	5.0	+465/−400	+170/−161
16	6	110	9120	34	8.0	+4099/−2159	+718/−620
18	7	69	14454	90	8.0	+62496/−8172	+1890/−1498

William I. Hartkopf, Principal Investigator

1999–present	Astronomer	Astrometry Department, U.S. Naval Observatory
1996–1999	Associate Professor	Department of Physics & Astronomy,
1981–1999	Assistant Director	Center for High Angular Resolution Astronomy,
1981–1996	Research Astronomer	Georgia State University
1981	Ph.D. (astronomy)	University of Illinois at Urbana-Champaign

- author/coauthor of 36,000+ interferometric observations and 400+ binary star orbits
- editor of 5th and 6th USNO Orbit Catalogs, 1st – 4th Interferometric Catalogs
- President, IAU Commission 26 (*Binary and Multiple Stars*), 2003–06, VP 2000–03
- SOC co-chair and proceedings editor-in-chief, IAU Symposium 240, *Binary Stars as Critical Tools and Tests in Contemporary Astrophysics*, Prague IAU GA, August 2006

Brian D. Mason, Co-Investigator

1997–present	Astronomer	Astrometry Department, US Naval Observatory
1994–1997	Postdoctoral Fellow	CHARA, Georgia State University
1994	Ph.D. (astronomy)	Georgia State University

- Over 100 nights speckle interferometry, long baseline optical interferometry, or adaptive optics on large telescopes and dilute aperture arrays.
- Has made observations of double stars yielding 11,475 mean positions in the WDS.
- Has calculated orbits of binary stars, 75 of which are considered the best orbit available, and six of which are qualitatively classified as “definitive.”

Relevant Publications (merged list):

- Mason, B.D., Gies, D.R., Hartkopf, W.I., Bagnuolo, Jr., W.G., ten Brummelaar, T., & McAlister, H.A. 1998, *ICCD Speckle Observations of Binary Stars. XIX. An Astrometric/Spectroscopic Survey of O Stars*, AJ **116**, 821
- Hartkopf, W.I., Mason, B.D., Gies, D.R., ten Brummelaar, T., Moffat, A.F.J., Shara, M.M., & Wallace, D.J. 1999, *ICCD Speckle Observations of Binary Stars. XXII. A Survey of Wolf-Rayet Stars for Close Visual Companions*, AJ **118**, 509
- Fekel, F.C., Scarfe, C.D., Barlow, D.J., Hartkopf, W.I., Mason, B.D., & McAlister, H.A. 2002, *The Quadruple System Mu Orionis: Three–Dimensional Orbit and Physical Parameters*, AJ, **123**, 1723
- Turner, N.H., ten Brummelaar, T.A., Roberts, Jr., L.C., Mason, B.D., Hartkopf, W.I., & Gies, D.R. 2008, *Adaptive Optics Photometry and Astrometry of Binary Stars. III. A Faint Companion Search of O-Star Systems*, AJ, in press (July)
- Mason, B.D., Hartkopf, W.I., Gies, D.R., & Henry, T.J. 2008, *The High Angular Resolution Stellar Multiplicity of Massive Stars*, in preparation

Budget:

• Direct Costs – Labor			
1. Wages (WIH): 160 hours @ $45.05		$7,208	
2. Wages (BDM): 80 hours @ $46.38		$3,710	
3. Fringe benefits (28% of wages)		3,057	
Total Direct Costs			**$13,975**
• Other Direct Costs			
1. Travel: two people to AAS meeting, 7-11 June 2009, Pasadena CA			
a. airfare	$400		
b. airport shuttle, other travel	50		
c. rental car: 5 days @ $40	200		
d. lodging: 5 nights @ $118	590		
e. meals: 6 days @ $64	384		
f. registration	325		
total per person	1949		
total travel expenses (shared rental car)		$3698	
2. publication costs: one 6-page AJ paper @ $105/page		630	
3. computer hardware: Dell Precision M4300 laptop		2031	
4. materials and supplies (toner cartridges, paper, etc.)		100	
Total Other Costs			**$6,459**
• Indirect Costs			
1. Overhead (32% of wages)		$3,494	
Total Indirect Costs			**$3,494**
• **Total Cost**			**$23,928**