Solar Analogs: Characteristics and Optimum Candidates

Discussion Sessions: Results and Transcripts

The Tuesday Solar Analogs workshop schedule was:

Panel discussion, 8:30-10:00
Working Groups 1, 10:30-noon
Working Groups 2, 1:00-2:30
Plenary Session, 3:00-4:30

In the two working group sessions, attendees divided into 5- to 6-member groups to debate specific questions on issues relevant to the workshop. There were five groups in each working group session. Between the second working group session and the plenary session, the results from the ten group meetings were compiled into tables on transparencies by the SOC (Hall, Lockwood, & Radick) and the plenary session moderator (White). These were presented for debate by the entire workshop during the plenary session.

On Tuesday, therefore, we tried to move from individual opinions (of the panelists) to opinions of small groups (the working groups) to the opinion of the entire workshop (during the plenary session). In this final section of the proceedings, we present the results that emerged from this process.

Description of working groups

As is obvious from the preceding section, the panel discussion gave us quite a bit to think about. Following the coffee break, we began the first of two working group sessions. There were five groups in both the morning and afternoon working group sessions; they were comprised of four or five attendees and were moderated by Ayres, Buzasi, Garrison, Lockwood, and Wade.

Each of the five working groups was given the same set of three questions. The specific questions appear below, but the general issues raised in each were as follows.

- **Question 1: What have workers done so far?** Given the guidelines that (a) solar analogs and/or twins must be identified on the basis of well-defined observational parameters, and (b) our direction for future research in this area will be clearest with a firm understanding of how the subject has developed over the past two decades, we ask *which observational parameters have been used in finding solar analogs, and with what degree of success*, and *which parameters have been ignored thus far?*

- **Question 2: Where do we go from here?** What are the best observational parameters to use in defining true solar twins, and which of these are essential? Is it possible to rank the most desirable parameters in order of preference, thereby setting up some kind of filter for defining a true solar twin?

- **Question 3: What is the best current solar twin?**

So that the SOC would have some chance of compiling the results from ten working groups (two sessions of five groups each) into a coherent whole, the moderators were supplied with standardized, quantitative forms. Although some of the questions did not lend themselves ideally to quantization, this at least gave the workshop a firm starting point at the plenary session.

On the following pages, we have tabulated the results and comments made by each group in response to the questions. The group format was a relaxes, 75-minute, roundtable discussion that the moderators [theoretically] kept moving along. In fact, our moderators did a wonderful job of corralling the opinions of their group members, and the somewhat experimental format of this part of the meeting turned out to be quite successful.

The working groups were (groups 1-5 morning, 6-10 afternoon, moderators in brackets):

1: [Ayres], Corbally, Giampapa, Skiff, Soderblom
2: [Buzasi], Dobson, Guinan, Hall, Rottman
3: [Garrison], Cayrel, Glushneva, Harvey
4: [Lockwood], Guedel, Howard, Henry, Henry, de Mello, Schleicher
5: [Wade], Franz, Friel, Grundy, Radick, White
6: [Wade], Dahn, Glushneva, Guinan, Howard, Schleicher
7: [Ayres], Cayrel, Guedel, de Mello, White
8: [Buzasi], Franz, Friel, Corbally
9: [Garrison], Grundy, Radick, Rottman, Skiff
10: [Lockwood], Giampapa, Hall, Harvey, Soderblom

The next section contains
- a detailed description of the questions posed to the working groups, and their responses,
- the results from all working groups, combined into summary tables, and
- an editorial summary of these data.

Working group results

Question 1: The Solar Twin Search So Far: Solar twins have been selected on the basis of specific observational parameters, and there are a large number of these to choose from.

[1A] How have the following parameters been employed in the solar analog hunt to date, and what has been the success or failure in identifying solar analogs in terms of those parameters?

Moderators evaluated their group's response and ranked the opinions on a scale of 5 (highly successful) to 1 (completely unsuccessful), or zero (not applicable). In addition, they noted the level agreement among the group by a σ that ranged from zero (unanimous agreement) to three (significant disagreement). In the table below, we list the twenty parameters given to the groups for discussion. Each group evaluated four parameters, so that each parameter was evaluated independently, in the morning and afternoon, by two different groups of astronomers.

Table 1. Parameters that have been used to find solar analogs/twins

Parameter	Group	Ranking	Remarks
T_{eff}	1	3 ± 2	Useful if spectroscopically derived, usually in a differential context
	6	4 ± 1	Concern over spread of T_{eff} measures. Depends on model quality
$\log g$	5	3 ± 2	Important, always available, but indirect
	10	0 ± 0	
M_{bol}	5	5 ± 1	Fundamental
	10	5 ± 0	
$B - V$	2	2 ± 1	Good for finding analogs; poor for finding twins
	7	4 ± 0	High utility as a guide, exists for many stars
Johnson $\neq B - V$	4	3 ± 0	
	9	3 ± 1	Relative ranking of homogeneous data OK.
V magnitude	4	0 ± 0	Not relevant
	9	4 ± 1	M_v very important; therefore m_v is important.
[Fe/H]	3	4 ± 0	
	8	4 ± 0	Not a good parameter for first cut.
$v \sin i$	5	2 ± 0	Allows you to differentiate the young stars. More needed!
	10	0 ± 0	
Inclination	4	0 ± 0	
	9	0 ± 0	Has been ignored *to date*; maybe interesting for future.
Microturbulence	3	1 ± 1	
	8	0 ± 0	Important, but subtle. Probably not important for $\odot$ twin search.
B field	5	1 ± 0	What many people are after, but not used to find $\odot$ analogs
	10	0 ± 0	
MK type	3	5 ± 0	
	8	5 ± 0	Good first cut for general search, but must recognize limitations
Cousins	1	4 ± 1	$V - I$ useful, but not as good as $b - y$ for fainter stars
photometry	6	2 ± 1	Not used except as transformed to Johnson. Maybe better than $B - V$
Strömgren	2	5 ± 0	Far superior to UBV; gives $m1$ and $c1$ indices
photometry	7	3 ± 2	$b - y$ not much employed
Energy	1	3 ± 2	Pretty useless: not enough + sys. errors. But, fundamental quantity
distribution	6	2 ± 0	Not enough stars for which this is available
Photometric	1	3 ± 2	Ancillary parameter
variability	6	1 ± 0	Viewed as a proxy for "activity" or youth
Spectroscopic	2	1 ± 0	Not utilized efficiently yet
variability	7	0 ± 0	Not for screening purposes, but useful as ancillary quantity
R'_{HK}	2	4 ± 1	Useful *if* you closely examine the photospheric contribution
	7	3 ± 2	Surrogate for age, but not very accurate. Starting point/screening
Location	4	2 ± 0	Space motions
	9	1 ± 0	*except* as cluster membership determinant
Space velocity	3	2 ± 1	
	8	2 ± 0	Might indicate place of origin, but not good for first cut.

> [1B] Are there any relevant parameters that have so far been ignored (both in the literature and in the list of 20 parameters supplied to the working groups) or inadequately considered, and what would be the specific insights gained from considering them? Determine up to two that are most important.

Working groups were asked to select one or two of the most important neglected parameters in the solar analog hunt so far, and to summarize the specific insights to be gained from using those parameters as selection criteria. The results are compiled in Table 2 below. Each parameter is lsited in a separate row, with the number of groups mentioning it and their remarks included in the second and third columns.

Table 2. Parameters that have been neglected in searching for solar twins.

Parameter	#[a]	Insights to be gained from using this parameter
Companionship	6	In terms of stellar and/or planetary companions
L_X	4	More broadly: parameters that measure activity in higher levels of the atmosphere, e.g., UV, Mg II h&k.
UV spectrophotometry	3	
Radio luminosity	2	10 cm: variable, sensitive to spots
Geneva photometry	1	More precise measurements than Johnson & different from Strömgren.
Detailed abundances	1	i.e., CNO, He, not just [Fe/H]
Galactic orbit	1	Useful combination of location and velocity
Convection	1	The group feels this is an underappreciated parameter in evolution/interior models
P_{rot}	1	
Intellegent [sic] life	1	

[a] Number of times this parameter was cited by working groups

Question 2: The Solar Twin Search Following This Workshop: What is the optimum method for searching for solar twins?

[2A] Which, if any, parameters *must* be used in any search for solar twins (determine up to four)?

Groups listed up to four parameters they considered essential in future searches for solar analogs and twins. Again, a one-to-five scale was used to indicate the level of agreement (or lack thereof) among the group members.

Table 3. Parameters/techniques that must be considered in future solar twin searches

Parameter	Rankings (group #)
M_V	5 (2), 5 (4), 5 (5), 5 (6), 5 (7), 5 (8), 5 (10)
Metallicity	5 (4), 3 (5), 5 (6), 5 (7), 5 (8), 5 (10)
Activity	4.5 (3), 5 (4), 3 (5), 5 (6), 5 (9), 5 (10)
P_{rot}	5 (2), 5 (7), 5 (8)
T_{eff}	4.5 (3), 5 (4), 5 (5), 5 (6), 5 (10)
Stromgren photometry	4 (2), 5 (8), 4 (9)
MK Type	4.5 (3), 4 (9)
Parallax (distance)	4.5 (3), 5 (9)
High-res spectroscopy	4 (2)
Mass	1 (7)
Age	1 (7)
Hour angle	1 (5)[a]

[a] Acknowledged by group during plenary session as "a joke."

[2B] Do the parameters employed depend on the research needs of the investigator, e.g., would an investigator working with UV data have fundamentally different search criteria than one working in the IR?

YES!

[C] Can (or should) the essential parameters identified in [A] above be ranked in order of preference? That is, what is the optimum, properly ordered set of "filters" for identifying solar twins?

Table 4. Should the essential parameters be ranked in order of preference?

Group #	Remark
2	No. It depends on the research needs of the investigator.
6	Only to the extent that they can be separated.
7	No. All are important at once.
10	No.

Table 5. If the parameters are ranked, in what order are they placed?

Group #	1^{st}	2^{nd}	3^{rd}	4^{th}
2	M_V	Strömgren	Hi-res spectroscopy	P_{rot}
3	MK Type	$T_{eff}, \log g$, metallicity	π/Distance	Activity
4	Color	M_V	Metallicity	Age
5	T_{eff}	M_V	P_{rot}	Composition
6	T_{eff}	M_V	Metallicity	Activity
8	Colors	M_V	Composition	Rotation
9	MK Type	Strömgren	M_V	Activity

Question 3: Optimum Candidates Rank the following stars (listed by HD number) in order of preference as solar twins, to the extent that the working group considers feasible and/or useful. Each group may add up to 2 stars to the list. The stars are: 1835 (9 Cet), 11131, 20630 (κ Cet), 28099 (VB 64), 44594, 76151, 86728, 89010, 114710 (β Com), 144585, 146233 (18 Sco), 186408 (16 Cyg A), 186427 (16 Cyg B), 187923A, 217014 (51 Peg).

Table 6. Remarks about individual stars

Star	Comments
1835	Good analog for *young* Sun; too late, too young
10307	Deserves study
11131	A little too hot; worth keeping; young; good analog, poor twin
20630	Too young; G5 V; poor analog
28099	Hyades member; analog, *NOT* twin; too young
44594	worth following up; young; HIPPARCOS π OK?; good analog
76151	Probably too young; too active; S too high; binary?
86728	Worth keeping in spite of MK type; too red; too problematic
89010	Too bright, too evolved; too bright
114710	Too young, too active, too hot; too active
144585	Too evolved; too luminous
α Cen A	Twin of 186408; analog, not twin
146233	A keeper; best of the bunch
186408	Older than Sun; analog, not twin; good twin
186427	Older than Sun; analog, not twin; good twin
187923A	Abundances too far off; spectral type off
217014	Good candidate!

Table 7. Optimum solar twin candidates

Rank	Order listed by working groups								
1	146233	146233	146233	146233	146233	146233	146233	146233	146233
2	217014	186408	186408	186408	217014	186408	186408	186408	186427
3	186408	186427	186427	217014	186427	186427	186427	186427	186408
4	186427	28099	217014	89010	44594	217014	217014	143761	217014
5	44594			1835			44594	28099	
6	86728			11131	186408				
7	76151			76151	α Cen A				
8	α Cen A			186427	11131				
9	144585				10307				
10	20630				76151				
11	28099				187923				
12	89010								
13	1835				1835				
14	114710				20630				
15	187923A				28099				

Review of Working Group Results and Plenary Session Discussion

This section is an editorial review of the results in Tables 1 through 7, as well as the discussion of those results during the plenary session (the transcript of the plenary session debate is in the following section of these proceedings).

1 From twenty parameters to four

Dick White, the plenary session moderator, opened the discussion by pointing out a principal component analysis (PCA) recently carried out by Andrea Dobson and Bob Donahue[2], in which the authors find that four parameters, as opposed to the canonical three, are required to decribe a star.

In preparing the plenary session presentations, White distilled the information in Table 1 into the following.

Table 1A. Data of Table 1 as shown in plenary session

Parameter	Rankings	Parameter	Rankings
T_{eff}	$3 \pm 2,\ 4 \pm 1$ *	V magnitude	$0 \pm 0,\ 4 \pm 1$
Cousins photometry	$4 \pm 1,\ 2 \pm 1$ *	$v \sin i$	$2 \pm 0,\ 0 \pm 0$
$B - V$	$2 \pm 1,\ 4 \pm 0$ *	Inclination	$0 \pm 0,\ 0 \pm 0$
Strömgren photometry	$5 \pm 0,\ 3 \pm 2$ *	Microturbulence	$1 \pm 1,\ 0 \pm 0$
R'_{HK}	$4 \pm 1,\ 3 \pm 2$ *	**B** field	$1 \pm 0,\ 0 \pm 0$
[Fe/H]	$4 \pm 0,\ 4 \pm 0$ *	Energy distribution	$3 \pm 2,\ 2 \pm 0$
MK type	$5 \pm 0,\ 5 \pm 0$ *	Photometric variability	$3 \pm 2,\ 1 \pm 0$
Johnson $\neq B - V$	$3 \pm 0,\ 3 \pm 1$ *	Spectroscopic var.	$1 \pm 0,\ 0 \pm 0$
M_{bol}	$5 \pm 1,\ 5 \pm 0$ *	Location	$2 \pm 1,\ 1 \pm 0$
$\log g$	$3 \pm 2,\ 0 \pm 0$	Space velocity	$2 \pm 1,\ 2 \pm 0$

Any parameters given a combined ranking ≥ 6 by the working groups received an asterisk, as shown above. The choice of 6 as a cutoff score was arbitrary, and the numbers themselves were produced by ten independent groups. The rankings were debated for some 20 minutes during the plenary session, but in the end, Radick pointed out that the asterisked quantities did in fact reduce to four parameters: five temperature or temperature equivalent, two luminosity or equivalent, one activity parameter, and composition. Thus, this part of the debate finished full-circle, with a confirmation, at least in this extemporaneous setting, of Dobson & Donahue's four-parameter result. Garrison pointed out that the redundancy available along the four axes of this parameter space was invaluable for consistency checks.

2 From four parameters to two

Only two parameters emerged in Table 1 with a ranking of "5" from both groups that discussed them, where "5" meant that parameter has been essential and highly beneficial in solar analog surveys over the past few decades. These were the star's MK spectral type, and its bolometric luminosity. Perhaps the MK result is unsurprising, since the Sun defines G2 V, but clearly there has been significant insistence that a posited solar twin closely resemble the Sun, in the spectroscopic sense defined by the MK system.

As a supplement to a near-solar MK type, the star's absolute energy output, M_{bol}, emerged as a prime requirement for selecting a solar twin. However, the absolute energy *distribution* was rated lower, even though it was cited as perhaps the most important observational quantity one could obtain. Concerns were raised about (1) systematic errors in the calibrations and (2) the lack of a large number of stars for which good energy distributions are available. White and Hall demurred, pointing out that very large compilations of stellar energy distributions, which agree well with published distributions for standard stars, have been made by the Russian groups and are largely unknown in the West. However, Lockwood also noted that

[2]Dobson, A. K., & Donahue, R., 1998, *How Many Parameters Are Needed to Describe a Star?: Principal Component Analysis as an Astrophysical Tool*, to appear in *The Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, R. A. Donahue and J. A. Bookbinder, eds.

published energy distributions for the Sun itself are in poor agreement, so we might expect some difficulty in identifying a solar twin in that sense.

Other parameters on the list were rated lower because of a recurring concern, launched by Buzasi during the panel discussion, that even if a quantity is of fundamental importance to understanding the character of a star, it is useless to us if it cannot be measured precisely or yields ambiguous results. Spirited debate revolved around [Fe/H], which has been widely employed in solar analog searches but for which different workers have obtained different results for the same objects.

3 On the mandate and pitfalls of huge databases

Several photometric parameters were given in the list of parameters, and this produced (1) a specific call for a shift in photometric systems and (2) a more general note of caution regarding the inertia a well-established and huge database of observations can develop.

Discussion of the various photometric parameters given in the list produced strong agreement regarding the use of Strömgren photometry in selecting solar analogs. The Strø"mgren system was generally agreed to be somewhat more desirable than the Cousins system, and far superior to Johnson. The venerable $B-V$ was simultaneously lambasted as much too metallicity-sensitive, and praised for the vast number of stars for which it has been determined. But Skiff drew attention to the work of Erik Olsen, who has performed Strömgren photometry of tens of thousands of solar-like stars. Other systems were mentioned (e.g., Tycho and Geneva), but there was little support for the observing effort required to develop the databases on those systems to the level that has been achieved with Johnson and Strömgren.

Inevitably the question arose as to *why* Olsen's work, for example, was not more familiar to the attendees, and why, if $B-V$ was good only as a rough guide for finding solar-like star, a shift to $b-y$ as the standard had not taken place years ago. The circular answer, of course, was that we use the huge $B-V$ database because that is the huge database we have had. Two serious reservations exist about following this path.

First, the scope and undeniable value of such a database often creates a mandate for its use, and can overly constrains investigators' perspectives. The more a database such as $B-V$ grows, the harder it becomes to shift to another standard of measurement, even if that standard is a superior quantity.

Second, and perhaps more insidious, is what happens once a quantity has been used and measured by many different investigators, using different instruments, referenced to different standard stars. The data from these many references can easily be placed in a blender and mixed into a large database, but, as Garrison pointed out in detail during the panel discussion, the resulting potion may well be lethal. Extreme caution in the selection of standard stars and the use of a standardized database is essential; or, if various references are combined, scrupulous attention to the discussions of calibrations and errors that the authors must provide if their paper is to be considered useful.

4 Neglected parameters

Having dispensed with essential and useful parameters, the workshop turned to those that have been so far ignored; the results are summarized in Table 2.

The most popular parameter in Table 2 was *companionship.* Some confusion surfaced as to whether the working groups had meant companionship in the sense of binarity and the circumstellar environment, or the presence of planets. Both were accepted as interesting parameters to apply to solar twins. Guinan suggested that components of wide, non-interacting binaries (e.g., the α Cen system) could be included in solar analog lists.

A clear demand for the incorporation of space-borne satellite observations of solar-like stars emerged in discussions of Question 1B (cf. Table 2), asking which quantities have been neglected in the solar analog search. Selection of solar analogs has so far been mostly with optical and near-UV data, yet as Rottman discussed in his talk, the relative variability of the Sun becomes increasingly pronounced at shorter wavelengths, exceeding a factor of 10 at coronal wavelengths. A significant problem here is the lack of time-series UV and X-ray data for numerous stars, the large IUE database notwithstanding. Extension of the "other-than-optical" idea into the radio regime also appeared twice on the working groups' lists.

There was general acknowledgment that the neglect of the parameters above has been technology-limited. At the time Hardorp initiated the solar analog search, IUE had just been launched, and high-precision planetary detections (e.g., Marcy and Mayor) were still in the future. However, the consensus was that current and planned solar and stellar space-borne observatories could and should used to study the upper atmospheres of solar twin candidates in detail.

5 Four parameters again

Given that the current state of affairs is not entirely satisfactory, where should we go from here? This was the focus of Question 2 (results in Tables 3, 4, and 5), which asked working groups to identify parameters that must be used in any future solar twin searches, and to rank them if the group considered it useful or desirable.

The essence of Tables 3 through 5 is (1) we have been more or less on the right track, and (2) we are best served by a conservative approach to selecting our solar twins.

Table 3 shows the 1-to-5 rankings assigned by different groups (group numbers are given in parentheses). No parameters were supplied *a priori*; groups were free to choose whatever four they thought were most important. Examination of the first five entries in Table 3 yields the same result as that in Table 1: there is luminosity (M_V), abundance (metallicity), activity (assuming "activity" and "P_{rot}" to be related), and temperature. Duplicate parameters appear in the rest of the entries. In agreement with the attendees' opinions in Table 1, Strömgren was the *only* photometric system mentioned in this part of the discussion. The general irreverence of the attendees in debating these weighty matters appear in the final entry of Table 3.

A significant number of the working groups (4 out of 10) explicitly said that a ranking of the desirable parameters was not possible, supporting the general feeling that (a) a solar twin must embody as full a description of the star as possible, which appears to require four parameters, and (b) different researchers will have different requirements of their solar twins (see, e.g., Wade's panel presentation, and the unanimous response to Question 2B).

Those groups that did rank the parameters took a conservative approach. Four out of seven chose "colors" or "MK Type" as most important parameter; "colors" were agreed in the plenary session discussion to mean well-defined, homogeneous databases of, e.g., Strömgren colors. Two of the remaining three groups ranked Strömgren colors second. A strong sentiment therefore emerges for whittling down the stellar sample with well-defined, well-behaved guides before proceeding to specific discriminants such as abundances, rotation rate, and effective temperature. The bolometric luminosity also reappears here as one of the parameters one *must* know.

6 And the winner is...

Fifteen frequently-cited solar analogs were given to the working groups for evaluation and ranking, to settle the issue (for at least the next six months) of which star is our current best solar twin. Table 7 speaks for itself; the following points stand out.

(1) The star 18 Sco (HD 146233 = HR 6060) is the clear winner, being placed first on every group's list.

(2) Four stars appeared consistently at the top of most lists. These top four have been separated by a line in Table 7. They are 18 Sco, 16 Cyg A & B (HD 186408 and 186427) and 51 Peg (HD 217014).

(3) A second, less well-defined group of four appears between rankings 5 and 8. These include HD 44594 (a former candidate for best solar twin), α Cen A, and HD 76151. A few interlopers appear in this group as well.

(4) Most of the remaining stars on the lst given to the working groups appear between rankings 9 and 15. These include the Hyades stars (HD 1835 and van Beuren 64) and others which are known to be young and highly active.

(5) Two stars, α Cen A and HD 10307, were not on the initial list, but were recommended by at least one group as targets deserving of further study.

Cayrel de Strobel suggested that the terms *solar-like star*, *solar analog*, and *solar twin* be applied to stars that increasingly closely resemble the Sun, with the last term only applied to those that are nearly indistinguishable from the Sun in terms of any parameter one observes. Table 7 likewise falls into three well-defined parts. Only the first four stars were considered reasonable solar twins by the workshop, with 18 Sco superior to the other three.

Below ranking 4, we move from the realm of solar twins to solar analogs. Workers using the results of this workshop can probably use stars in the lower part of Table 7 for applications where solar-analogous stars are required, but with a greater degree of caution to the literature regarding that star than might be needed for the twins. The star HD 44594, for example, is slightly evolved, while HD 76151 has larkedly greater chromospheric activity than does the Sun. For some applications, this might be irrelevant, but the purists at the workshop labeled these star as decidedly unsolar in at least one important way.

The stars below ranking 8 were placed there wth almost no dissension. The question asked working groups to rank "twins" rather than analogs, and there was no question that these stars cannot be considered twins. Many of the participants ranked these stars as solar analogs, though there are a few (the very active HD 1835, and κ Cet (G5V), for example), that might well be demoted to the realm of solar-like stars.

7 Conclusion

The solar analog search began in 1978, when Johannes Hardorp published *The Sun Among the Stars. I. A Search for Solar Spectral Analogs.*[3] A vitriolic debate concerning the veracity and pitfalls of Hardorp's method developed, and *The Sun Among The Stars. III.*[4] is a bitter tract in which the science is overshadowed by Hardorp's acerbic responses to his critics. In 1985, Bob Garrison wrote that Hardorp "set out, with good intentions, to fnd a solar analog...[but] he has muddied the waters considerably."[5] In 1998, during the panel discussion at our workshop, Garrison told us that Hardorp visited him in Toronto six months before his death and said, "Bob, you were right."

These were the four most telling words of the workshop, for they remind us that we tread on very delicate ground. Without Hardorp's pioneering papers, and the tremendous effort he devoted to inventing this line of inquiry for the rest of us, our workshop probably would not have happened. But "You were right" must have been an unhappy conclusion to reach at the end of one's life.

Throughout the workshop, and these proceedings, we see calls for extreme caution in working through this very complex subject. We have the exhaustive effort de Mello and da Silva have expended on one single star, Garrison's comments regarding calibration of standards and indiscriminate culling of the literature, Soderblom's remarks about the curious state of some of the HIPPARCOS parallaxes, Farnham & Schleicher's dramatically divergent reflectance spectrum of Ganymede, and Burlov-Vasiljev's plots of the substantial discrepancies in different attempts to measure the energy distribution of the Sun itself. Several times during the workshop, we heard the forlorn comment that picking a solar twin was nearly impossible because the Sun doesn't even always look like the Sun.

During the discussion after her talk, Giusa Cayrel stated that "We are not done." The Solar Analogs Workshop certainly did not solve the problem, but we selected a current best solar twin, and we defined the problems we must solve more clearly. We hope the next two decades of solar analog research will benefit.

[3] A&A, 1978, 63, 383

[4] A&A, 1980, 91, 221.

[5] in IAU Symposium 111, *The Calibration of Fundamental Stellar Quantities* (Dordrecht: Reidel), ed D. S. Hayes et al., p. 25

Discussion during the plenary session

Moderated by O. R. White (HAO)

White: All right, may we start? I think there was a principal component analysis that Andrea Dobson did, stating that you should be able to define, or describe a star using four parameters, using an ideal four-dimensional phase space. Now we've gone through this exercise today, and I'll tell you: the dimensions have increased a lot [laughter] in trying to track the Sun through all these parameters that we think are various strengths, and interests, and necessities. So what I'd like to do is just move down through the questions. We've tallied the responses as best we can in the past few minutes, and the individual group leaders will have to respond to and defend choices presented on these viewgraphs. Fortunately, we haven't identified any names on these [laughter], so you won't be fingered immediately. Let's just see how far we get, and see if we can come up with some description or rationale for how we improve our selection of solar-analogous stars. So here's Question 1A...

Question 1: The Solar Twin Search So Far: Solar twins have been selected on the basis of specific observational parameters, and there are a large number of these to choose from.

[1A] How have the following parameters [*four different parameters were given to each working group, for a total of 20 under consideration*] been employed in the solar analog hunt to date, and what has been the success or failure in identifying solar analogs in terms of those parameters?

White: Now [putting up Table 1A (page 183)] to help you through this blizzard of numbers [laughter], we marked parameters with an asterisk where the rankings of the two groups that evaluated them, on the one-to-five scale, totaled six or more. [General laughter.] Yes, I know it's a little bit arbitrary. And I'm not going to worry about the standard deviations, I'm sorry; they're a nuisance [laughter]!

Wade: Just like an astronomer: throw out the error bars [laughter].

White: I say we throw out the whole thing and go have a drink [laughter]. Okay, effective temperature, $B-V$, other Johnson colors, Strömgren photometry, Cousins photometry, R'_{HK}, composition, MK type, and luminosity are the ones that come to the top as being the ones most used. You can see the relative rankings of the others, along with some rather derisive comments at right [laughter]. For example, for energy distribution it says, "Useless, but fundamental" [laughter]!

Ayres: Um, excuse me...

White: Now, I think we...

Ayres: *Excuse me-e-e-e*, that was from my group in the morning, and the whole point is that from a remote sensing point of view, the energy distribution is actually the most fundamental quantity there is. But from a practical point of view, forget it! You have to rely upon color for most purposes.

White: I agree. There was continuous discussion in the groups I was in about what was a fundamentally measurable quantity, and what you had to infer by going through models. Now, there are nine of these 20 parameters that people ranked pretty highly as being widely used. Are there any comments or disagreements?

Garrison: Wouldn't you need the same comment for M_{bol} as you have for energy distribution?

Soderblom: And how do you get M_{bol} if you don't have the V magnitude?

Garrison: Right, exactly.

White: Fundamental, but useless [laughter]?

Soderblom: No, not useless. How can V be listed up there as "not relevant" and M_{bol} as fundamental?

Ayres: I guess we were thinking you'd have V and a bolometric correction...

Franz: And you'd better have a parallax, too.

Soderblom: I would take issue with listing temperature as a "derived quantity". Of all these different things you can determine for a star, there's not very many you can determine in a direct sense for the Sun. But *temperature* is one them. You can argue about whether or not you get an absolute temperature or not, but I don't care: you can get differential effects very nicely. So I happen to like T_{eff}.

Buzasi: I'd like to point out that at least the way we were interpreting things in my group, the question was "What has been useful?", not "What could be useful?"

Soderblom: Well, T_{eff} *has* been useful.

Buzasi: Yes, definitely.

White: It's one of the principal things that has been used, to specify the zone on the HR diagram where we want to look. Any more comments?

Wade: Is anyone surprised?

White: I'm not particularly surprised. Well, one thing that did surprise me, and this is just out of ignorance, is the demand here for Strömgren photometry.

Skiff: It should be used more than it is.

White: This will come up over and over again: we all, in our individual fields, have these historical indices or measures that we're comfortable with and have used for a long time. As time goes on, we figure out better ways to do it, but it's hard to make the shift and still keep everything tied together, because you wind up doing it all continuously from that time on. My favorite case is the sunspot number, which drives me up the wall because it's not physically interpretable. But, it's the longest continuously-measured solar activity index we have.

Rottman: It looks like one of the groups picked $B-V$ and the other one didn't, and the other one picked Strömgren and gave less weight to the Johnson side. Maybe it goes back to this question of what has been *historically* used.

Ayres: Strömgren is superior.

White: Superior, yes, but there's a lot of *experience* based on $B-V$.

Ayres: Our group said basically, there's this *huge* historical database based on Johnson $B-V$, and so naturally it has been used; however, the Strömgren colors are much better because they're not as sensitive to metallicity.

White: Everybody agree with that? [Chorus of "Yes"s.]

Soderblom: We're evolving into the Strömgren system.

Wade: What about the Tycho system?

Soderblom: Well, we haven't checked it out, we haven't had a chance to absorb it yet.

White: What, you mean there's *another* system?

Hall: There are infinite systems [laughter].

White: So the consensus is, if we could, we'd shift to the Strömgren system from this time forward?

Ayres: Yes, exactly, definitely.

Wade: What prevents us from doing that?

Soderblom: Nothing! It's being done.

Skiff: Erik Olsen has observed all the HD stars brighter than 8.5 between A5 and G5. It's done. It's 40,000 stars. It's beautiful. It's a series of A&A supplement papers; the first one is in volume 54, page 55.

Guinan: I know it [laughter].

Skiff: That one's got 30,000 stars. The advantage of the Strömgren system is that you can separate the metallicity...

Schleicher: Do we know the value of the Sun in that system?

Skiff: Yes, look at my poster.

Garrison: Dick, you were concerned before about there being more than four parameters. Some of these are redundant, so it may not be more than four parameters.

White: We do want to get around to the lowest potential phase space, eventually.

Radick: I think there's exactly four parameters up there, out of the nine you flagged with the asterisks. In a broad sense, there are five of them that are either temperature or some equivalent of temperature, there are two that are luminosity or equivalent to it, there's one composition and one activity. So there really are four.

White: Let's work through that...

Radick: OK, there's composition, and activity, each mentioned once. There's M_{bol} and MK spectral type, which are both basically luminosity, and the other five are all temperature in some way.

White: So we're down to the four fundamental ones that you always come to. We're just seeing the different names, the different techniques that have been invented for approaching the same intuitive physical quantity.

Garrison: That's wonderful. It's a good thing we have those checks on the same quantity.

White: Well, now that we're back to four, can we move on?

Wade: Who was the second group considering rotation period? They said "3" and the first one said "N/A".

Soderblom: The question was asking about "use of this parameter to select solar analogs up to this point. We know nothing about rotation, nothing, so that's where the not applicable came from.

Wade: Fine, I agree with the N/A, so where did the second group's "3±0" come from?

Soderblom: Darned if I know.

Ayres: It's only the extremes of rotation that would be important anyway.

White: All right. Question 1B says...

> **Question 1: The Solar Twin Search So Far:** Solar twins have been selected on the basis of specific observational parameters, and there are a large number of these to choose from.
>
> [1B] Are there any relevant parameters that have so far been ignored (both in the literature and in the list of 20 parameters supplied to the working groups) or inadequately considered, and what would be the specific insights gained from considering them? Determine up to two that are most important.

White: It's hard to get all this on one viewgraph in a sensible way, but we'll do it anyway.

[Puts up Table 2 (p. 180). Pause. General laughter; the first item says "intelligent life".]

White: I thought the first one was a hoot. As we filled out these viewgraphs, the thought came out that it maybe shouldn't be intelligent life, but *silly* life. So, what we think is missing is X-ray observations, 10-cm radio, UV spectrophotometry, rotation, Geneva photometry...now that's something I don't know, yet another system.

Soderblom: It's in some sense relatively esoteric, and we're not going to go out and do 40,000 stars all over again on a different system.

White: So we stay with Strömgren as the most reliable, best-defined system.

Soderblom: Tom, I thought we added companionship to the list.

Ayres: Yes in fact, in both of my groups, companionship came out as an important factor.

Garrison: We added companionship as well.

[General babble of agreement.]

White: Yes, I just missed that in making the viewgraph, but there's an important point: were we considering companionship in the sense of binary systems, or in the sense of planets? My groups were discussing the planetary side of it as interesting for solar-type stars, but you needed to know about binary systems to discriminate against them.

Garrison: I like using the word "environment."

Soderblom: Yes, you could be talking about extensive circumstellar material, for example.

Rottman: I'm showing my ignorance here, but what about the 10.7-cm radio entry?

Garrison: Either X-ray or radio could be used as an interesting discriminant for solar-type stars.

Ayres: Yes, but how many solar-type stars have 10.7-cm radio measurements?

Garrison: That's the point, radio is a nice one we could add as an approach for finding analogs.

Guinan: But the radio is so feeble, and X-ray would do the same job.

Garrison: But not many people have sat on a star in X-rays, to see if it's in a low activity cycle.

Ayres: You can't even detect them in the radio, though.

Skiff: You apparently can't detect them in X-rays, either, not ordinary activity?

Guinan: Yes, you can.

Soderblom: Not in survey mode.

Garrsion: Maybe radio and X-ray are redundant.

Guinan: Look, radio you just can't do. The Sun is a *feeble* radio source. Put the Sun out just five parsecs away, and it's gone. There's no existing radio telescope that could possibly pick it up.

White: What about UV spectrophotometry? That one got a lot of votes.

Lockwood: I was avoiding that one, the UV absolute energy distribution, because of the extreme sensitivity of the measurements, like the ones Dave Schleicher does, to discrepancies from the "perfect solar analogy."

Wade: We're not talking about transition region material here, right?

White: No, it's ground-based, so it's from 4000 Angstroms down to the ozone cutoff.

Ayres: Dick, our group was thinking more of the mid-UV, say 2000 to 3200 Angstroms.

Wade: Convection is up there as a desirable. Is that something that can be used, really, as a tool for finding solar analogs?

Ayres: You'd use line bisectors, the kind of thing that David Gray is doing – high-resolution spectroscopy and analysis of line asymmetries.

Wade: So this would be for detailed study of the physics of the surface of the star, not a screening tool.

White: Good. Now going down to Question 2A, which is...

Question 2: The Solar Twin Search Following This Workshop: What is the optimum method for searching for solar twins?

[A] Which, if any, parameters *must* be used in any search for solar twins (determine up to four)?

White: [Shows Table 3, p 181.] Okay, I've listed all the groups' opinions, and what the "8 x 5" means, for example, is that for M_{bol} there were eight ratings of "5", and then there was some wag who put 4.5 [laughter]. The rest of this is pretty straightforward. A lot of votes for rotation, colors, composition got a lot of votes. The ones that fall off the wagon are mass and age. So...Tom?

Ayres: From a fundamental point of view, you really are interested in stellar evolution. Mass, age, and composition should uniquely determine the state of a star. So our group picked those, instead of, say, rotation, which is correlated with age to some extent.

Rottman: I'm a little confused by the trick question here: I read the question to mean, which four things would be the best discriminants, if you only used four.

Garrison: No, we took it as meaning which parameters would you insist upon before you declared a star a solar analog. In other words, if a reliable measure of just one of the four parameters were missing, you wouldn't be able to say the star was a solar analog.

Ayres: And the difficulty is, of course, that mass is almost impossible to determine for groups of stars, even though it's absolutely fundamental, and the same thing goes for age. We know the age of one star, the Sun. We have to move over to proxy information when we go to the stars.

Wade: Which is why you use temperature and luminosity to stick the star on an HR diagram and read off mass and age. So, in the sense that colors, and T_{eff}, and MK type are all different ways of plotting the x-axis of the HR diagram, those have about the same total weight as M_{bol}.

Soderblom: I see $\log g$ up there. I would argue that $\log g$ is pretty useless.

Garrison: Well, $\log g$ is what you really get.

Soderblom: You can't get really $\log g$ very well out of spectra.

Garrison: You can't get M_{bol} either.

Ayres: You can't get enough accuracy on mass out of a $\log g$ determination.

Buzasi: Activity and rotation are both up there, and they're clearly related. You can argue about how tight that relation really is. Activity is nominally easier to measure. Rotation is, I would say, more fundamental.

Ayres: That's only true among stars that are fairly close to the Sun.

Buzasi: Well, that's what I'm talking about; we've already narrowed the field down. You're not measuring rotation in early A stars here. I'm talking about twins, not analogs here.

Hall: Going back to the conclusion from the first question, I notice if you allow "Strömgren" and "colors" to mean the same thing here, you get the same result.

Buzasi: A difficulty here is that some of these things are numbers that you measure, and others are techniques.

White: Okay, good. Think you can pull a summary out of this, Jeff?

[Silence.]

[General laughter.]

White: Shall we press on?

Question 2: The Solar Twin Search Following This Workshop: What is the optimum method for searching for solar twins?

[B] Do the parameters employed depend on the research needs of the investigator, e.g., would an investigator working with far-UV data have fundamentally different search criteria than one working in the IR, and *how* would these needs differ?

White: This was not controversial at all; the answer was quite simple. YES! We ran into this in both discussions, that there were clear differences in need depending on what you were looking at. It just comes down to admitting that those differences are there, and out of our list, making sure we have the fundamental parameters that really describe the star.

Soderblom: It also depends on what you're looking *for*, that is, your science needs.

White: Yes, the one that came up in particular was whether the star had a companion or not. Are you a SETI person, in which case discarding companionship is not the ideal criterion.

Question 2: The Solar Twin Search Following This Workshop: What is the optimum method for searching for solar twins?

[C] Can (or should) the essential parameters identified in [A] above be ranked in order of preference? That is, what is the optimum, properly ordered set of "filters" for identifying solar twins?

White: Now, this is the set of answers [puts up Table 5, p. 181]. You can see there are different preferences in the order here, but there's some obvious commonality, which we expect. You see M_{bol} and effective temperature showing up across the board, as they should. Composition appears frequently. There's another demand for Strömgren colors, and perhaps a somewhat surprising demand for rotation and activity.

Wade: It seems that sometimes the Strömgren colors are used as a temperature discriminant, and sometimes as a metallicity discriminant. For instance, in the rightmost column, you've got MK type, which is your basic temperature criterion, and then Strömgren modifying it.

Garrison: Yes, you've got MK, Strömgren, and colors, which are all ways of getting at T_{eff}. So you can boil this down somewhat.

Wade: I'm also interested in that group's rankings: what is it about Strömgren that puts it higher than M_{bol}?

White: I would put M_{bol} higher myself.

Garrison: Well, Strömgren is well-determined and M_{bol} is not.

Wade: M_{bol} is sort of a measurable quantity.

Garrison: Aww, come on, have you determined M_{bol} lately?

Rottman: In five of these columns I see a lot of similarity, but in the leftmost one, we have high-resolution spectroscopy sitting in there, and I was wondering why that group put it there. What exactly did they feel you'd get?

Buzasi: I think it was our way of rolling a lot of different things into one. We were trying to squeeze as much information into our four parameters as possible. High-resolution spectroscopy is something from which you get, for example, compositions.

Wade: So how do you determine, from your spectrum, whether or not the star is a solar analog? What measurement do you make?

Buzasi: Temperature, [Fe/H].

Soderblom: How about, for things like 18 Sco, looking to see if the spectrum looks the same?

Wade: Hmm, so what do we do, a little "chi by eye," or...

Garrison: You don't need high resolution to see if the spectrum looks the same.

Schleicher: When it comes right down to it, of the first three parameters in the rankings there, two of them have to define the star's position on the axes of an HR diagram. In every case. And the third one is composition. And the remaining one is activity, or age.

White: Well, there's the same process again, we're going down this one little track through the phase space. All right, let's go to the lottery here...

Question 3: Optimum Candidates Rank the following stars (listed by HD number) in order of preference as solar twins, to the extent that the working group considers feasible and/or useful. Each group may add up to 2 stars to the list. The stars are: 1835, 11131, 20630, 28099, 44594, 76151, 86728, 89010, 114710, 144585, 146233, 186408, 186427, 187923A, 217014.

White: [puts up Tables 6/7, p. 182.] Well, here's the ranking. You'll see there's a big cutoff after about four stars. Within those, there's 18 Sco, 51 Peg, 16 Cyg A and B. They come in different orders. I'm a little interested in why the one group ranked B over A. But in the groups I was in, I know there was a general feeling that the top four were good solar twins, and below that we started to consider the stars more to be solar analogs.

Buzasi: Yes, we actually drew a line under those four.

White: I also see VB 64 in here twice, and that's a surprise.

Guinan: Yes, why is that there? It's an analog, not a twin.

Ayres: Well, it's photometrically very similar.

Guinan: But the age is clearly different.

Garrison: The metallicity is different.

[Numerous comments, amounting to general denouncement of VB 64.]

Guinan: When you have a twin, it isn't just height [laughter]. It's weight, age...

White: DNA, whatever.

Schleicher: It had *better* be the same age!

Hall: I was wondering why so many groups ranked 16 Cygni A above 16 Cygni B. After all, B was the one that Hardorp explicitly called "the perfect solar spectral analog," and it subsequently was analyzed in great detail, so B is the one you traditionally think of as the slightly better analog.

Garrison: Who does? I never have.

Guinan: B is better. I don't think it matters. I just think people didn't care what order they put them in. I've always thought B was closer to the Sun than A.

Hall: Okay, that's what I was asking: were groups really ranking them that way, or just writing them down as a pair.

Guinan: But they're older than the Sun. They're 7 billion years old, and a bit more luminous. They're not good twins, but there hasn't been much else to use.

Garrison: Perhaps if you're looking a for a good example of what the Sun will become.

White: Okay, just to clean up the diagram, is everyone happy with VB 64 where it is?

[Further vociferous denouncement.]

Wade: You know, I don't see the Sun on that list anywhere [laughter].

Guinan: The one that really concerns me is HD 44594, which lost its twinship on the basis of a Hipparcos parallax.

Garrison: I think it *should* lose its twinship. It doesn't look very good.

Skiff: HD 44594 is slightly evolved.

Soderblom: Well, the two groups who put on VB 64 are clearly out of order; they were incompetent [laughter].

White: We have four excellent candidates here, and I think that represents a pretty good consensus.

Rottman: One group ranked 16 Cyg B very low, though; it's way down at number 8. Is there a reason for that?

Friel: That was our group, and the reason was that we were looking almost exclusively based on the data supplied in the table [in the meeting materials], without updating the data using more recent results. So if you just ranked them on the table data, that's where B ended up; but in our discussion we agreed it should be higher.

White: Any more comments? Well then, that about does it.