A compiled catalogue of optical positions of extragalactic radio sources

Jinling Li and Wenjing Jin

Shanghai Observatory, Shanghai 200030, China

Received January 2; accepted April 15, 1996

Abstract. — Based on 28 individual catalogues, in which the positions of optical counterparts of extragalactic radio sources are listed, we compiled a combined catalogue by means of a weighted least squares adjustment. The catalogue is in the system of FK5/J2000.0. It consists of about five hundred sources, among which there are 56 primary sources with position uncertainties as $0''.09$. Comparisons show that the orientation differences between optical and radio frames are $A_1 = -0''.013 \pm 0''.012$, $A_2 = 0''.077 \pm 0''.012$, $A_3 = 0''.005 \pm 0''.009$. Local relative deformations are not obvious within the precision of ground-based optical observations.

Key words: astrometry — reference frames — catalogues — radio continuum: galaxies

1. Introduction

The distant and compact extragalactic radio sources with almost no proper motions are ideal celestial bodies to implement the quasi inertial celestial reference frames. Since the number of compact extragalactic radio sources is limited to several hundreds and most of them have very faint optical counterparts (about 18 mg), the radio celestial reference frame is only qualified as the first class quasi inertial reference frame. Optical reference frame will be still widely used in practise. Therefore it is important to compare the radio frame with the optical frame.

The fundamental method of this comparison is implemented through observing common celestial bodies (e.g. extragalactic radio sources with optical counterparts) in the two kind of frames. By analyzing the observations of common objects, we can determine the orientation differences and the local relative deformations between radio and optical frames and then establish the linkage between them.

Some observations of optical counterparts published since 1960 are collected and analyzed in this paper. By systematic corrections and system transformation, the observations are unified to the system of FK5/J2000.0 and a combined catalogue consisting of 510 optical counterparts is deduced. Orientation differences and local rela-

tive deformations between the combined catalogue and the IERS/VLBI reference frame are analyzed.

2. A brief introduction to the collected data

A lot of scientists have been devoting themselves to the comparison between optical and radio reference frames. Observations of optical counterparts of extragalactic radio sources have been published successively. Data collected and used in this paper are listed in Table 1, where Cols. 1 to 8 represent respectively the sequence number of data (Seq.), the author(s) (Author), the number of sources (Nb.), the declination range (Dec. Range), the formal uncertainties in right ascension and in declination (rms R.A.(s), Dec.(")), the reference catalogue (Ref.C.) and the reference epoch (Ref.Epoch). All the observations are obtained by photographic plates.

The distribution of 510 optical counterparts at the epoch of B1950.0 in the Aitoff projection is shown in Fig. 1, in which circles, triangles and asterisks represent respectively the positions of 387 sources with one observation, 60 sources with two observations and 63 sources with more than two observations. From this figure it is clear that the sky coverage of the sources are deserved to be improved.

3. Unification of reference systems

Though most of the observations (in Table 1) are referred to Perth 70 or AGK3, which are based on the system of FK4/B1950.0, the system of FK5/J2000.0 is presently the widely adopted fundamental system. Therefore, the

Table 1. The observations of optical counterparts of extragalactic radio sources

Seq.	Author	Nb.	Dec. Range ($^{\circ}$)	rms		Ref.C.	Ref. Epoch
				R.A.(s)	Dec.(")		
1	Murray et al.,1971	16	4.8 -- 77.2	0.0231	0.137	FK4	B1950.0
2	Argue & Kenworthy,1972	21	4.8 -- 77.2	0.0176	0.137	AGK3	B1950.0
3	Barbieri et al.,1972	46	-14.6 -- 71.8	0.0253	0.301	AGK3/SAO.	B1950.0
4	de Vegt & Gehlich,1978	17	2.3 -- 69.8	0.0040	0.048	FK4	B1950.0
5	Walter & West,1980	24	-44.5 -- -0.1	0.0196	0.324	Perth70	B1950.0
6	West & Walter,1981	39	-44.5 -- 5.2	0.0150	0.213	Perth70	B1950.0
7	Costa et al., 1983	22	-44.5 -- 1.8	0.0138	0.175	Perth70	B1950.0
8	Harrington et al.,1983	10	-8.9 -- 69.8	0.0034	0.050	FK4	B1950.0
9	Geffert & Richtler,1983	4	20.2 -- 69.8	0.0055	0.033	AGK3	B1950.0
0	Torres et al.,1984	23	-44.1 -- 11.9	0.0122	0.181	Perth70/AGK3	B1950.0/J2000.0
A	Walter & West, 1986	50	-44.5 -- 5.3	0.0146	0.215	Perth70	B1950.0
B	Geffert et al.,1989	21	7.4 -- 69.8	0.0100	0.120	Brorf(Fk4)	B1950.0/J2000.0
C	Dick & Kumkova, 1990	11	-0.3 -- 44.9	0.0163	0.283	AGK3	B1950.0
D	White et al., 1990	14	-39.7 -- -0.3	0.0117	0.196	Perth70	J2000.0
E	Ma et al., 1990	28	0.4 -- 71.4	0.0043	0.050	FK5	J2000.0
F	Brosche et al.,1991	4	2.3 -- 79.7	0.0210	0.056	AGK3	B1950.0
G	Assafin & Martins,1992	10	-75.2 -- -25.0	0.0242	0.228	Perth70	B1950.0
H	Assafin & Martins,1992	10	-75.2 -- -25.0	0.0210	0.207	PPM(FK5)	J2000.0
I	Costa & Loyola, 1992	26	-75.2 -- 12.6	0.0105	0.125	Perth70/AGK3	B1950.0
J	Russell et al, 1992	4	-29.3 -- -9.7	0.0035	0.050	FK5	J2000.0
K	Veron & Veron, 1975	130	-41.6 -- 80.5	0.4500	0.4500	AGK3	B1950.0
L	Clements, 1981	103	-13.1 -- 79.7	0.0107	0.1165	SAO/AGK3	B1950.0
M	Wroblewski et al.,1981	22	-76.5 -- 2.3	0.0130	0.1714	Perth70	B1950.0
N	Jauncey et al., 1989	6	-77.1 -- -47.7	0.0332	0.1800	Perth70	B1950.0
O	Xu et al., 1990	3	2.3 -- 71.4	0.0063	0.1167	AGK3	J2000.0
P	Harvey et al., 1992	8	-77.1 -- -47.7	0.0300	0.1787	Perth70	J2000.0
Q	Russel et al., 1991	8	-1.7 -- 63.8	0.0041	0.0500	FK5	J2000.0
R	White et al., 1991	97	-79.0 -- 0.0	0.0502	0.3167	Perth70	J2000.0

Fig. 1. The distribution of 510 optical counterparts at the epoch of B1950.0 in the Aitoff projection

observations should be unified to the system of FK5/J2000.0. The procedure of the transformation to FK5/J2000.0 has been thoroughly studied and results from related studies (Aoki et al. 1983; Kaplan 1981; Smith et al. 1989; Huang et al. 1991; Schwan 1985; Jin et al. 1991) are directly used in our calculation.

4. The compilation of the combined catalogue

After the systematic unification, remaining differences among individual catalogues are usually statistically studied by basing on a large number of common objects. But we cannot act the same way to deal with the observations of the optical counterparts because there are only a few common sources among individual catalogues. Therefore a method used by IERS for merging of catalogues of radio source positions (Arias et al. 1988; IERS 1992) is applied in our computation, i.e. the remaining differences are expected to be further reduced by applying small angle rotations among observations.

In order to secure that there are sufficient equations to determine unknowns and taking into consideration the sky coverage, the number of sources, the observation precision as well as the precision of reference catalogues, 28 individual catalogues listed in Table 1 are divided into definition, densification and complementary catalogues, corresponding to sequence number from 1 to J , K to P and Q to R respectively. All the sources are classified into primary, secondary and complementary sources. Primary sources are those common to at least three definition catalogues;

Table 2. Relative rotations from each individual catalogue to the combined one. Unit:1''

Seq.	Nb.	A_1	A_2	A_3
1	8	-0.23 ± 0.08	-0.41 ± 0.09	-0.09 ± 0.11
2	10	-0.16 ± 0.07	0.06 ± 0.07	-0.06 ± 0.08
3	12	0.03 ± 0.09	-0.47 ± 0.09	0.33 ± 0.08
4	15	0.00 ± 0.04	0.07 ± 0.04	-0.15 ± 0.03
5	16	0.27 ± 0.09	0.03 ± 0.11	-0.16 ± 0.08
6	26	-0.02 ± 0.06	0.00 ± 0.06	0.02 ± 0.05
7	15	0.43 ± 0.08	-0.02 ± 0.07	-0.07 ± 0.06
8	9	-0.04 ± 0.04	0.12 ± 0.04	-0.04 ± 0.03
9	4	-0.19 ± 0.05	0.00 ± 0.05	-0.27 ± 0.05
0	13	0.34 ± 0.09	0.30 ± 0.12	0.00 ± 0.06
A	30	0.07 ± 0.06	0.03 ± 0.06	0.02 ± 0.05
B	13	-0.05 ± 0.06	0.03 ± 0.06	-0.12 ± 0.05
C	6	-0.09 ± 0.05	0.01 ± 0.10	0.14 ± 0.08
D	5	-0.19 ± 0.14	-0.16 ± 0.18	0.18 ± 0.09
E	18	0.05 ± 0.04	0.14 ± 0.04	-0.08 ± 0.03
F	3	-0.02 ± 0.05	-0.12 ± 0.06	-0.39 ± 0.05
G	7	-0.10 ± 0.11	-0.15 ± 0.12	0.24 ± 0.14
H	7	0.00 ± 0.11	-0.04 ± 0.11	0.27 ± 0.13
I	8	-0.33 ± 0.09	0.33 ± 0.07	-0.07 ± 0.06
J	3	0.23 ± 0.09	0.25 ± 0.09	0.30 ± 0.08
K	7	0.14 ± 0.21	-0.67 ± 0.24	-0.32 ± 0.19
L	3	-0.08 ± 0.08	0.17 ± 0.11	-0.29 ± 0.07
M	3	-0.35 ± 0.20	-0.20 ± 0.19	-0.14 ± 0.11
N	2	0.06 ± 0.21	0.16 ± 0.17	0.49 ± 0.38
O	2	0.17 ± 0.13	0.22 ± 0.10	0.00 ± 0.07
P	2	0.07 ± 0.18	0.24 ± 0.14	0.62 ± 0.32
Q	2	0.52 ± 0.02	0.35 ± 0.14	-2.95 ± 0.13
R	4	-0.44 ± 0.37	0.08 ± 0.20	1.21 ± 0.54

secondary sources are those common to at least two individual catalogues but are not in the list of primary sources; complementary sources are those in only one of the individual catalogues.

The coordinates (α_i, δ_i) of the i th primary source in the combined catalogue and the relative rotations (A_{1j}, A_{2j}, A_{3j}) from the j th definition catalogue to the combined one are determined simultaneously from a set of equations as follows:

$$\begin{aligned}
 & -A_{1j} \cos \alpha_{ij} \tan \delta_{ij} - A_{2j} \sin \alpha_{ij} \tan \delta_{ij} \\
 & \quad + A_{3j} + \alpha_i = \alpha_{ij}, \\
 & A_{1j} \sin \alpha_{ij} - A_{2j} \cos \alpha_{ij} + \delta_i = \delta_{ij}, \\
 & \Sigma A_{1j} = 0, \\
 & \Sigma A_{2j} = 0, \quad j = 1, \dots, J \text{ (in Table 1)} \\
 & \Sigma A_{3j} = 0.
 \end{aligned} \tag{1}$$

where $(\alpha_{ij}, \delta_{ij})$ are the coordinates of the i th primary sources in the j th definition catalogue. The orientation of the combined catalogue is defined by the last three equations of Eq. (1).

Rotations of densification catalogues to the combined one are determined from primary sources. For complementary catalogues, which do not contain any primary sources, the rotations are based on secondary sources. Coordinates of secondary and complementary sources are de-

termined by applying orientation corrections to individual catalogues.

All the calculations are weighted based on formal uncertainties of observations. Residuals are tested by the χ^2 -test (A small additive variance and a modest multiplicative factor are applied to compute the "true" standard errors and therefore to bring the reduced χ^2 close to unity). Equations are solved with the Singular Value Decomposition method (Press et al. 1986).

Orientation differences between each individual catalogue and the combined one are listed in Table 2, from which it can be concluded that some of the angles are significant within the precision of ground-based optical observations. Coordinates of primary sources in the combined catalogue are listed in Table 3, where Cols. 1 to 10 show respectively the IAU designations of sources, the status of sources, the coordinates, the estimate of coordinate uncertainties, the individual catalogue which contains the source, the type of source, the optical magnitude and other designation of the source.

5. Discussion

There are 510 sources in the combined catalogue (CAT.QSO), which is in the system of FK5/J2000.0. Internal precision is $0''.088$, $0''.256$, $0''.377$ in $\alpha \cos \delta$ and $0''.093$, $0''.232$, $0''.374$ in δ for 56 primary sources, 62 secondary sources and 392 complementary sources respectively. Rotations from CAT.QSO to RSC (IERS) 93 C 01 (IERS 1993) based on the 56 primary sources are as follows:

$$\begin{aligned}
 A_1 &= -0''.013 \pm 0''.012, \quad A_2 = 0''.077 \pm 0''.012, \\
 A_3 &= 0''.005 \pm 0''.009.
 \end{aligned}$$

Studies by Arias et al. (1995) have shown that the FK5/J2000.0 is aligned with the IERS/VLBI reference frame to about 70 milliarcsec. Therefore, the above rotation angles indicate that the 56 subset of the combined catalogue is reasonably tied to the FK5/J2000.0 system.

Acknowledgements. The authors are indebted to T.Q. Xu, S.H. Wang and P.Z. Lu for helpful discussions. Our thanks also belong to all the observers who have made the observations used in this study. We express our thanks to Dr. H.G. Walter for his valuable comments in reviewing the text and his kindly suggestions to improve the text.

References

- Aoki S., Soma M., Kinoshita H., Inoue K., 1983, A&A 128, 263
- Argue A.N., Kenworthy C.M., 1972, MNRAS 160, 197
- Arias E.F., Charlot P., Feissel M., Lestrde J.-F., 1995, A&A 303, 604
- Arias E.F., Feissel M., Lestrde J.-F., 1988, in: BIH Annual Report for 1987, Observatoire de Paris, Paris, p. D-113

Table 3. Coordinates of primary sources in CAT.QSO

Source	STS (1)	Right Ascension			Declination			Uncertainty(2)		IC (3)	TTS (4)	Mg.	Other Name
		h	m	s	°	'	"	s	"				
0106+013	P	1	8	38.7618	1	35	0.222	0.0050	0.094	360AC	Q	18.5	4C+01.02
0134+329	P	1	37	41.2916	33	9	35.159	0.0081	0.092	123	Q		3C 48
0150-334	P	1	53	10.1160	-33	10	25.826	0.0078	0.106	67I	Q	18.6	
0237-233	P	2	40	8.1989	-23	9	15.867	0.0058	0.095	60AJ	Q	16.6	PHL 8462
0316+413	P	3	19	48.1466	41	30	42.204	0.0037	0.042	289BE	G	12.7	3C 84
0332-403	P	3	34	13.6872	-40	8	25.215	0.0064	0.096	560AGH	Q	17.5	
0333+321	P	3	36	30.0935	32	18	29.247	0.0032	0.046	8BE	Q	17.0	NRAO 140
0336-019	P	3	39	30.9592	-1	46	35.966	0.0071	0.115	560A	Q	17.9	CTA26
0402-362	P	4	3	53.7972	-36	5	1.468	0.0073	0.101	567AGH	Q	16.0	
0420-015	P	4	23	15.8189	-1	20	32.888	0.0057	0.104	560D	Q	17.5	
0430+052	P	4	33	11.0822	5	21	15.638	0.0029	0.044	60AEI	Q	15.0	3C 120
0438-436	P	4	40	17.2056	-43	33	8.753	0.0094	0.131	50A	Q	19.5	
0440-003	P	4	42	38.6820	-0	17	43.764	0.0079	0.112	ACD	Q	18.5	NRAO 190
0518+165	P	5	21	9.8807	16	38	21.907	0.0035	0.058	124B	Q		3C 138
0537-441	P	5	38	50.3495	-44	5	8.860	0.0092	0.082	560AGH	Q	17.5	
0538+498	P	5	42	36.1274	49	51	7.287	0.0057	0.057	1234B	Q		3C 147
0605-085	P	6	7	59.6865	-8	34	51.378	0.0067	0.131	5AI	Q	16.5	OH 010
0607-157	P	6	9	41.0962	-15	42	42.066	0.0092	0.144	560A	Q	17.0	
0637-752	P	6	35	46.6555	-75	16	16.704	0.0315	0.124	GHI	Q	16.3	
0642+449	P	6	46	32.0071	44	51	16.636	0.0047	0.051	4CE	Q	19.0	OH 471
0735+178	P	7	38	7.3801	17	42	19.067	0.0029	0.053	4BE	Q	16.5	OI 158
0833+654	P	8	37	44.9562	65	13	34.918	0.0202	0.112	123	Q		3C 204
0835+580	P	8	39	6.4587	57	54	17.117	0.0148	0.114	123	Q		3C 205
0851+202	P	8	54	48.8656	20	6	30.488	0.0030	0.049	49BE	B	14.5	OJ 287
0923+392	P	9	27	3.0049	39	2	20.920	0.0032	0.049	48E	Q	17.5	4C39.25
1034-293	P	10	37	16.0814	-29	34	2.653	0.0095	0.098	67A	B	18.0	OL-259
1055+018	P	10	58	29.6049	1	33	58.687	0.0029	0.051	67ACEI	Q	18.3	OL 093
1104-445	P	11	7	8.6838	-44	49	7.626	0.0095	0.115	567A	Q	18.0	
1127-145	P	11	30	7.0142	-14	49	27.239	0.0086	0.124	567A	Q	16.9	OM-146
1144-379	P	11	47	1.4070	-38	12	11.190	0.0063	0.095	5ADGHI	Q	17.5	
1148-001	P	11	50	43.8740	-0	23	54.570	0.0083	0.130	357A	Q	17.6	4C-00.47
1219+285	P	12	21	31.6698	28	13	58.555	0.0034	0.049	4BE	B	15.0	ON 231
1226+023	P	12	29	6.6987	2	3	8.593	0.0026	0.045	3468AEF	Q	12.9	3C 273
1250+568	P	12	52	26.3495	56	34	19.655	0.0073	0.058	124	Q		3C277.1
1253-055	P	12	56	11.2123	-5	47	21.517	0.0083	0.114	3567A	Q	16.5	3C 279
1404+286	P	14	7	0.3951	28	27	14.735	0.0037	0.053	8BEF	G	14.0	OQ 208
1430-178	P	14	32	57.7113	-18	1	35.171	0.0064	0.110	67AD	Q	19.0	OQ-151
1442+101	P	14	45	16.4694	9	58	36.117	0.0035	0.057	40C	Q	18.5	OQ 172
1458+718	P	14	59	7.4959	71	40	19.838	0.0252	0.105	123	Q		3C 309.1
1510-089	P	15	12	50.5467	-9	5	59.473	0.0023	0.067	568AD	Q	16.7	
1519-273	P	15	22	37.6448	-27	30	11.045	0.0077	0.107	67A	Q	18.5	
1555+001	P	15	57	51.3967	-0	1	50.472	0.0083	0.109	60A	Q	19.0	DW 1555
1641+399	P	16	42	58.8169	39	48	37.142	0.0036	0.042	12348BCE	Q	16.3	3C 345
1730-130	P	17	33	2.7425	-13	4	50.188	0.0083	0.130	560A	Q	18.5	NRAO 530
1741-038	P	17	43	58.8703	-3	50	4.964	0.0088	0.123	567A	Q	19.0	
1807+698	P	18	6	50.6877	69	49	28.030	0.0084	0.044	489BEF	G	14.2	3C 371
1921-293	P	19	24	51.0798	-29	14	30.409	0.0063	0.079	67AJ	Q	17.5	OV-236
1933-400	P	19	37	16.2311	-39	58	1.956	0.0087	0.106	67AGH	Q	19.0	
2134+004	P	21	36	38.5870	0	41	54.130	0.0033	0.058	67AE	Q	18.0	OX 057
2155-152	P	21	58	6.3074	-15	1	9.750	0.0057	0.087	AIJ	B	17.0	OX-192
2200+420	P	22	2	43.2974	42	16	39.953	0.0032	0.046	3489BE	B	14.0	BL Lac
2201+315	P	22	3	14.9776	31	45	38.168	0.0036	0.054	4BE	Q	14.5	4C 31.63
2230+114	P	22	32	36.4134	11	43	50.868	0.0034	0.064	30E	Q	17.3	CTA 102
2251+158	P	22	53	57.7452	16	8	53.487	0.0026	0.050	24BE	B	16.1	3C454.3
2326-477	P	23	29	17.7073	-47	30	18.973	0.0131	0.147	GHI	Q	17.5	
2345-167	P	23	48	2.5923	-16	31	11.898	0.0104	0.147	67A	Q	18.5	OZ-176

Notes 1. STS: status of the source. P: primary; S: secondary; C: complementary.

2. Estimation of uncertainties.

3. IC: Individual catalogue in which the source is available.

4. TTS: type of the source. Q: quasar; B: BL Lac object; G: galaxy.

- Assafin M., Martins R.V., 1992, A&AS 93, 247
- Barbieri C., Capaccioli M., Ganz R., Pinto G., 1972, AJ 77, 6, 444
- Brosche P., Ducourant C., Galas R., Geffert M., Karafistan A., 1991, A&A 245, 669
- Clements E.D., 1981, MNRAS 197, 829
- Costa E., Loyola P., 1992, A&AS 96, 183
- Costa E., Torres C., Wroblewski H., 1983, A&AS 51, 425
- Dick W.R., Kumkova I. I., 1990, IAU Symp. 141, 453
- Geffert M., Richtler T., 1983, A&A 118, 201
- Geffert M., Tucholke H.-J., Walter H.G., Moreno M.A., Ivanova V., et al., 1989, A&A 224, 323
- Harrington R.S., Douglass G.G., Kallarakal V.V., Smith C.A., 1983, AJ 88, 1376
- Harvey B.R., Jauncey D.L., White G.L., Nothnagel A., Nicolson G.D., 1992, AJ 103, 229
- Huang Tianyi, Xia Yifei, 1991, Act. Astron. Sinica 32, 258
- IERS, 1992, 1991 IERS Annual Report, Observatoire de Paris, Paris, p. II-15
- IERS, 1993, 1992 IERS Annual Report, Observatoire de Paris, Paris, p. II-19
- Jauncey D.L., White G.L., Preston R.A., Niell A.E., Harvey B.R., et al., 1989, AJ 98, 49
- Jin W., Xu T., Lu P. Liao D., 1991, Influence of systematic differences of FK4 on determining earth orientation parameters. In: Hughes J.A., Smith C.A., Kaplan J.H. (eds.) Proc. IAU Collo. 127, Reference Systems. USNO, Washington, D.C., 280
- Kaplan G.H., 1981, USNO Circ. No. 163
- Ma C., Shaffer D.B., de Vegt C., Johnston K.J., Russell J.L., 1990, AJ 99, 1284
- Murray C.A., Tucker R.H., Clements E.D., 1971, Royal Obs. Bull. No. 162, 215
- Press W.H., Flannery B.P., Teukolsky S.A., Vetterling W.T., 1986, In: "Numerical Recipes: the Art of Scientific Computing", Pub. by the Press Syndicate of the Univ. of Cambridge, New York, 515
- Russell J.L., Jauncey D.L., Harvey B.R., White G.L., Reynolds J. E., et al., 1992, AJ 103, 2090
- Russel J.L., Johnston K.J., Ma C., Shaffer D., de Vegt C., 1991, AJ 101, 2266
- Schwan H., 1985, A&A 149, 50
- Smith C.A., Kaplan G.H., Hughes J.A., Seidelmann P.K., 1989, AJ 97, 265
- Torres C., Wroblewski H., Costa E., 1984, A&AS 58, 193
- de Vegt C., Gehlich U.K., 1978, A&A 67, 65
- Veron M.P., Veron P., 1975, A&A 42, 1
- Walter H.G., West R.M., 1980, A&A 86, 1
- Walter H.G., West R.M., 1986, A&A 156, 1
- West R.M., Walter H.G., 1981, A&AS 46, 277
- White G.L., Bunton J.D., Anderson M. W. B., Batty M.J., Brown D.R., Corben J.B., 1991, MNRAS 248, 398
- White G.L., Lestrade J.-F., Jauncey D.L., Phillips R.B., Preston R.A., Reynolds J.E., 1990, AJ 99, 405
- Wroblewski H., Costa E., Torres C., 1981, A&A 93, 245
- Xu Tongqi, Lu Peizhen, Wang Shuhe, Zhu Wen Yao, 1990, Acta Astron. Sinica 31, 267