A study of NIR atmospheric properties at Paranal Observatory
(Research Note)

G. Lombardi1, E. Mason2, C. Lidman3, A. O. Jaunsen4, and A. Smette1

1 European Southern Observatory, Casilla 19001, Santiago 19, Chile
e-mail: glombard@eso.org
2 ESA-STScI, 3700 San Martin Drive, MD 21218, Baltimore, USA
3 Australian Astronomical Observatory, PO Box 296, Epping NSW 1710, Australia
4 Institute of Theoretical Astrophysics, University of Oslo, PO Box 1029 Blindern, 0315 Oslo, Norway

Received 23 December 2010 / Accepted 29 January 2011

ABSTRACT

Aims. In order to maximize the scientific return of the telescopes located at the Paranal Observatory, we analyse the properties of the atmosphere above Paranal in the near-infrared (NIR).

Methods. We estimate atmospheric extinction in the spectral range 1.10–2.30 μm (J, J′, H, and Ks) using standard stars that were observed during photometric and clear nights with ISAAC on the Very Large Telescope UT1 between 2000 and 2004. We have built a database consisting of hundreds of observations, which allows us to examine how extinction varies with airmass and the column density of water vapour. In addition, we use theoretical models of the atmosphere to estimate Rayleigh scattering and molecular absorption in order to quantify their fractional contribution to the total extinction in each filter. Finally, we have observed 8 bright red standard stars to evaluate filter color terms.

Results. We find that extinction coefficients are <0.1 mag airmass−1 in all the considered bands. The extinction coefficient in the J-band strongly depends on the column density of water vapour. Molecular absorption dominates the extinction in J, H and Ks, while Rayleigh scattering contributes most to the extinction in J′. We have found negligible color terms for J, H and Ks and a non-negligible color term for J′.

Key words. atmospheric effects – Site testing

1. Introduction

The ESO Paranal Observatory is located on the edge of the Atacama Coast in Northern Chile, 120 km south of the city of Antofagasta, at an altitude of 2635 meters above sea level. The conditions at the observatory are characterised by a high fraction of clear nights and low levels of humidity (Lombardi et al. 2009), which are important for near-infrared (NIR) observations. However, there has been little direct measurement of the properties of the atmosphere above Paranal in the NIR.

In order to fill this gap, we have calculated the extinction coefficients using photometric standard stars observed with the Infrared Spectrometer And Array Camera (ISAAC) at the Very Large Telescope (VLT) Unit Telescope 1 (UT1) as part of the ISAAC calibration plan. In addition, we have estimated the fractional contribution of Rayleigh scattering, molecular absorption and aerosol scattering to the extinction. This estimation required the application of a theoretical approach retrieved from the literature. Finally, to complete the analysis, we also calculated the instrumental color terms using 8 red stars observed under photometric conditions.

2. Database and data reduction

Our dataset consists of standard star observations covering a period of 5 years (from March 2000 through to December 2004). The observations were made during clear nights with the ISAAC short-wavelength (SW) arm in J, J′, H, and Ks. All data, including the relevant calibration frames, were retrieved from the ESO archive. Clear nights were identified by inspecting the nightly observatory weather reports. All stars have magnitudes on the LCO system (Persson et al. 1998).

Table 1. Properties of ISAAC SW imaging filters used in this study.

| Filter | Central wavelength [μm] | Width [μm] | Width [%] |
|--------|-------------------------|------------|-----------|
| J      | 1.25                    | 0.29       | 23        |
| J′     | 1.24                    | 0.16       | 13        |
| H      | 1.65                    | 0.30       | 18        |
| Ks     | 2.16                    | 0.27       | 13        |

Notes. See http://www.eso.org/sci/facilities/paranal/instruments/isaac/doc/

Table 1 lists the characteristics of ISAAC filters (ISAAC User Manual 2009), while in Table 9, at the end of this Research Note, we note all the standard stars used in the analysis. The data reduction has been performed using the ISAAC Pipeline. Each frame has been corrected for electronic artifacts, dark subtracted and flat fielded. Each standard star is imaged over a grid of five positions, one just above the center of the array and one in each quadrant. The pipeline computes a set of instrumental magnitudes which are averaged to deliver the zeropoint (ZP) uncorrected for extinction.

ZP uncertainties are computed as σ = σZP / \sqrt{n}, where n is the number of times, usually five, a single standard is observed, and σZP is the scatter about the mean ZP reported by

1 mag airmass−1 in all the considered bands. The extinction coefficient in the J-band strongly depends on the column density of water vapour. Molecular absorption dominates the extinction in J, H and Ks, while Rayleigh scattering contributes most to the extinction in J′. We have found negligible color terms for J, H and Ks and a non-negligible color term for J′.

Key words. atmospheric effects – Site testing

ABSTRACT

Aims. In order to maximize the scientific return of the telescopes located at the Paranal Observatory, we analyse the properties of the atmosphere above Paranal in the near-infrared (NIR).

Methods. We estimate atmospheric extinction in the spectral range 1.10–2.30 μm (J, J′, H, and Ks) using standard stars that were observed during photometric and clear nights with ISAAC on the Very Large Telescope UT1 between 2000 and 2004. We have built a database consisting of hundreds of observations, which allows us to examine how extinction varies with airmass and the column density of water vapour. In addition, we use theoretical models of the atmosphere to estimate Rayleigh scattering and molecular absorption in order to quantify their fractional contribution to the total extinction in each filter. Finally, we have observed 8 bright red standard stars to evaluate filter color terms.

Results. We find that extinction coefficients are <0.1 mag airmass−1 in all the considered bands. The extinction coefficient in the J-band strongly depends on the column density of water vapour. Molecular absorption dominates the extinction in J, H and Ks, while Rayleigh scattering contributes most to the extinction in J′. We have found negligible color terms for J, H and Ks and a non-negligible color term for J′.

Key words. atmospheric effects – Site testing
Fig. 1. Evolution in time of the zero-points for $J$, $J_s$, $H$ and $K_s$. The solid vertical lines indicate M1 recoating events, while dotted vertical lines indicate ISAAC interventions.

the pipeline. In our analysis, we have rejected points having $\sigma > 0.050$ mag. Our final sample contains 575 data points in $J$, 603 data points in $J_s$, 604 data points in $H$ and 667 data points in $K_s$.

3. Data analysis

3.1. Time evolution of the zeropoint

In Fig. 1, the zeropoints of the four bands are shown as four time series. Different colors represent different bands. We clearly see that, for each band, the zeropoints are characterized by trends within well defined time intervals. A further inspection demonstrated that the intervals are delimited by technical or maintenance interventions, either on the instrument or the telescope (e.g. M1 recoating). This means that, in the mentioned intervals (or periods, $P$), the computed zeropoints are affected by deterioration of the telescope optics after a recoating of UT1 primary mirror (M1) or instruments troubles (ISAAC technical interventions). A list of the events that occurred between 2000 and 2005 is reported in Table 2.

The deterioration in the aluminum coating of the telescope mirrors is mainly due to dust and oxidation. It results in a progressive reduction in the mirror reflectivity, an increase in the thermal background emission (Frogel 1998) and a consequent decrease in the zeropoints. A change (increase or decrease) in the zeropoint can also be due to interventions onISAAC, as they affect the instrument configuration. Our idea was to consider each period separately and to remove, from each one of them, the time dependency by subtracting a linear fit of the zeropoint with time. In practice we adjust all zeropoints to the value of the intercept of the fit at the beginning of the considered period. During the analysis we have confirmed that a linear fit was accurate enough, therefore higher polynomials have not been used. The fits for periods P3 and P6 are not well constrained, because the small number of points within these two periods. Therefore, they are not been considered further in this analysis.

The evolution in the zeropoint within each period is fitted with

$$ZP(t) = Ct + ZP_0$$

where $t$ is the time, $ZP_0$ corresponds to the zeropoint at the beginning ($t = 0$) of the considered period, and $C$ the slope of the fit. The differences $ZP(t = 0) - ZP_i$ have been computed and added to each observed $ZP_i$.

Finally, in each period, we subtracted the intercept of the fit at $t = 0$ from the corrected $ZP_i$. In this way we have eliminated both the offset between periods and the evolution with time.

Table 2. Technical events occurred between 2000 and 2005.

| Item | Date     | Event            |
|------|----------|------------------|
| P1   | 2000 02 10 | M1 recoating     |
| P2   | 2001 03 27 | ISAAC intervention|
| P3   | 2001 08 21 | ISAAC intervention|
| P4   | 2001 10 14 | ISAAC intervention|
| P5   | 2002 03 14 | ISAAC intervention|
| P6   | 2002 11 25 | M1 recoating     |
| P7   | 2003 03 28 | ISAAC intervention|
| P8   | 2004 01 26 | ISAAC intervention|
| P9   | 2004 04 03 | M1 recoating     |
3.2. Effects of the precipitable water vapour

The transmission of the atmosphere in the NIR is greatly affected by the presence of water. Considering the classical Johnson filters, an increase in the column density of water vapour causes $J-K$ and $(H-K)$ to be bluer, because the effect of water vapour is stronger in $K$ ($\Delta \lambda = 0.41 \mu m$) than in $J$ and $H$ (Frogel 1998; see also Fig. 1 in Manduca & Bell 1979). On the other hand, the ISAAC $K_s$ filter has a narrower bandwidth ($\Delta \lambda = 0.27 \mu m$, see Table 1) and avoids the strongest water lines. Therefore we expect that, in our case, $J$ and $H$ will suffer more from large amounts of water in the atmosphere.

The amount of water above Paranal has been continuously monitored since July 2000 using the images from the Geostationary Operational Environmental Satellite (GOES). The sampling is every 3 h starting at 00h UT.

To retrieve the Precipitable Water Vapour (PWV) from GOES images a model exists developed by A. Erasmus under contract with ESO (Erasmus & Peterson 1997; Erasmus & Sarazin 2000; Erasmus & Sarazin 2002). The method is based on combining satellite current image in the 6.7 $\mu m$ and 10.7 $\mu m$ channel with wind and temperature profiles forecasted by a prediction center.

Typical satellite observations at about 6.5 $\mu m$ are sensitive to emissions from water vapour resident in the layer between about 600 mbar ($\sim$4400 m) and 300 mbar ($\sim$9000 m). For what concerns GOES vertical resolution, the 6.7 $\mu m$ channel is located near the center of a strong water vapor absorption band and under clear sky conditions it is primarily sensitive to the relative humidity averaged over a depth of atmosphere extending from 200 to 500 mbar (Soden & Bretherton 1993). The horizontal resolution is sufficient since the atmosphere surrounding Paranal is not expected to vary significantly over an area that extends several 10’s of km.

Figure 3 shows the yearly trend in the amount of PWV sampled at Paranal during photometric and clear nights. We do see a yearly periodic modulation with high values (up to 13 mm in 2002) in the trimester January-March corresponding to the so called Bolivian winter. As shown in the figure, the median PWV at Paranal during photometric and clear nights is 2.3 mm.

Figure 4 shows the relationship between zeropoints and the PWV in the considered bands. For each band we have calculated a weighted linear fit. The fits are repeated twice more after rejecting 3-$\sigma$ outliers. In Table 3 we report the slopes and the RMS of the fits. For $J_s$, $H$, and $K_s$ the trend with the column density of PWV is quite slight, while for $J$ it is very significant. The scatter about the best fit for $J$ is between 2 and 4 times larger that the scattered measured for the other filters.

### 4. Determination of the atmospheric extinction coefficients

The relationship between $ZP$ and airmass ($X$) defines the extinction curve (Bouguer curve). The extinction coefficient ($\kappa$) is the slope of a linear fit to this curve. The fit is done three times. Between each fit, 3-$\sigma$ outliers are rejected.

The extinction coefficients have been calculated in two different ways:

1. correcting the zeropoints for the amount of PWV before computing $\kappa$;
2. considering separately the zeropoints in different PWV ranges in order to evaluate $\kappa$ as a function of the PWV.

### Table 3: Zeropoints-versus-PWV slope and dispersion (RMS).

| Band | Slope [mag per unit of PWV] | Dispersion [mag] |
|------|-----------------------------|-----------------|
| $J$  | $-0.007 \pm 0.001$          | 0.048           |
| $J_s$| $-0.003 \pm 0.001$          | 0.024           |
| $H$  | $-0.003 \pm 0.001$          | 0.019           |
| $K_s$| $-0.002 \pm 0.001$          | 0.011           |

Within a period. This represents a clear advantage. We can now work with a single dataset, rather than 9.

It is interesting to check the variation in $ZP_0$ after each event. If the event did not affect the instrument performance, $ZP_0$ values should be all identical. As shown in Fig. 2, we observe significant offsets between events.

![Fig. 2. $ZP_0$ for each period.](image)

![Fig. 3. Monthly trend of the PWV on Paranal in photometric and clear nights.](image)
Table 4. Calculated $\kappa$ in [mag airmass$^{-1}$] for $J$, $J_s$, $H$ and $K_s$ at Paranal.

| Band | PWV-corrected ZP | PWV $= 0$–2 mm | PWV $= 2$–4 mm | PWV $= 4$–7 mm |
|------|------------------|-----------------|-----------------|-----------------|
|      | $\kappa$ disp.   | $\kappa$ disp.  | $\kappa$ disp.  | $\kappa$ disp.  |
| $J$  | 0.072 0.040      | 0.038 0.038     | 0.060 0.036     | 0.090 0.033     |
| $J_s$| 0.048 0.019      | 0.034 0.019     | 0.040 0.020     | 0.058 0.018     |
| $H$  | 0.034 0.015      | 0.035 0.015     | 0.030 0.015     | 0.053 0.016     |
| $K_s$| 0.043 0.013      | 0.040 0.015     | 0.046 0.014     | 0.042 0.012     |

5. The fractional contribution to the extinction

According to Hayes & Latham (1975) the largest contributors to atmospheric extinction are Rayleigh scattering ($\kappa_{\text{Ray}}$), molecular absorption ($\kappa_{\text{mol}}$) and aerosol scattering ($\kappa_{\text{aer}}$). The efficiency of aerosol scattering from particles that are smaller than a few microns at $\lambda > 1.0 \mu m$ is negligible (Lombardi et al. 2008), therefore for the ISAAC filters (Table 1) we have computed the vertical atmospheric extinction coefficients as the sum of $\kappa_{\text{Ray}}$ and $\kappa_{\text{mol}}$

$$k_\lambda = \kappa_{\text{Ray}, \lambda} + \kappa_{\text{mol}, \lambda}. \quad (4)$$

Variations in $k_{\text{Ray}}$ and $k_{\text{mol}}$ with time are linked to occasional and periodic climatic changes in the atmosphere above the site (Lombardi et al. 2009). For this reason, theoretical models are valid only to calculate average contributions to the extinction coefficients.

5.1. Rayleigh scattering

Rayleigh scattering of unpolarised light is due to particles with dimensions that are $\ll \lambda$. It has been extensively discussed by Penndorf (1957). According to Hayes & Latham (1975), Rufener (1986) and Burki et al. (1995) the vertical Rayleigh extinction can be expressed as

$$k_{\text{Ray}, \lambda} = B \lambda^{-4} \quad (5)$$

where the Rayleigh scattering coefficient $B$ is a complex function of the refractive index, $n(T, P, \lambda)$, and the number of particles,
to compute the expressions in Penndorf (1957) and Hayes & Latham (1975) have been measured at Paranal (Lombardi et al. 2009). We have used the HITRAN database (Rothman et al. 2009).

\( \kappa_{\text{mol}, \lambda} \) values are reported in Table 5.

Table 5. Rayleigh scattering coefficients and vertical Rayleigh extinction in [mag airmass\(^{-1}\)] calculated for Paranal.

| \( B(T, P, \lambda) \) | \( \kappa_{\text{Ray}, \lambda} \) |
|----------------|----------------|
| \( J \)       | 0.106 ± 0.011  |
| \( J_0 \)     | 0.109 ± 0.011  |
| \( H \)       | 0.035 ± 0.004  |
| \( K_s \)     | 0.012 ± 0.001  |

\( B(T, P, \lambda) \) and expressions for \( n, N \) and \( B \) are given by Penndorf (1957).

In the years between 2000 and 2004 a mean temperature of \((12.8 \pm 0.5) \degree \text{C}\) and a mean pressure of \((743.5 \pm 0.2) \text{hPa}\) have been measured at Paranal (Lombardi et al. 2009). We have used the expressions in Penndorf (1957) and Hayes & Latham (1975) to compute \( B(T, P, \lambda) \) and \( \kappa_{\text{Ray}, \lambda} \) for the four ISAAC filters. The values are reported in Table 5.

As expected, Rayleigh scattering is more efficient in \( J \) and \( J_0 \). It is an order of magnitude less efficient in \( H \) and \( K_s \).

5.2. Molecular absorption

The contribution to the extinction originating from molecular absorption was modeled using an IDL driver to the Reference Forward Model (RFM). RFM is a GENLN2-based line-by-line radiative transfer code developed by Anu Dudhia at the Atmospheric, Oceanic and Planetary Sciences Institute at Oxford University (UK) to analyse data from MIPAS on-board ENVISAT\(^1\). The code was run using the 2008 version of the HITRAN database (Rothman et al. 2009).

For the current work, only lines caused by H\(_2\)O, CO\(_2\), N\(_2\)O, CH\(_4\) and O\(_2\) were considered. We slightly modified the tropical atmospheric profile available with the RFM code to carry out simulations corresponding to a temperature of 12.8 \degree \text{C} and an atmospheric pressure of 743.5 hPa (Lombardi et al. 2009). The amount of water vapour was scaled to match the median PWV for Paranal (2.3 mm). The code also allows one to vary the airmass of the line-of-sight or to select a specific molecule.

The extinction in each filter was estimated by multiplying the \( \kappa \) calculated with the PWV rescaled \( Z_P \), while the gray zone is the dispersion (see Col. 2 of Table 4).

The dotted line represents the theoretical Rayleigh scattering coefficient in \( \text{mag airmass}^{-1} \), while the gray zone is the contribution to the extinction originating from molecular absorption.

5.3. Fractional contributions

In Col. 1 of Table 7, we list \( \kappa_I \) for \( J, J_0, H \) and \( K_s \). The values have been derived using equation (4) and the computed values for \( \kappa_{\text{Ray}, \lambda} \) and \( \kappa_{\text{mol}, \lambda} \). The uncertainties derive from the propagation of the uncertainties of \( T \) and \( P \) in Lombardi et al. (2009) and as to be assumed has an upper limit to the variation of the theoretical \( \kappa_I \).

\[ \frac{\kappa_{\text{Ray}, \lambda}}{\kappa_{\text{mol}, \lambda}} \]

\[ \frac{\kappa_{\text{Ray}, \lambda}}{\kappa_{\text{mol}, \lambda}} \frac{\kappa_{\text{mol}, \lambda}}{\kappa_{\text{mol}, \lambda}} \]

Fig. 6. Extinction coefficients in \( J, J_0, H \) and \( K_s \) calculated for PWV = 0–2 mm, PWV = 2–4 mm, PWV = 4–7 mm. The dotted line represents the \( \kappa \) calculated with the PWV rescaled \( Z_P \), while the gray zone is the dispersion (see Col. 2 of Table 4).

Fig. 7. Plots of \((m_{\text{cal}} - m_{\text{the}})\) versus \((J - K_s)\). The slope of the linear fit is \( C_m \) and is tabulated in Table 8.
For $J_s$, $H$ and $K_s$, there is good agreement between the theoretical $\kappa_d$ and the empirical $\kappa$ calculated from the PWV rescaled zeropoints (Col. 2 of Table 4). For the $J$-band, there is a significant discrepancy, which is due to the high opacity of the atmosphere at the red end of the $J$ filter. The red end of the $J$ filter is effectively defined by the atmosphere. Changes in the amount of PWV in the atmosphere shifts this edge, which leads to larger photometric uncertainties, as demonstrated by the large scatter about the best fits in Figs. 4 and 5. As noted in Sect. 4, this result demonstrates the importance of observing IR standards at
roughly the same airmass and at roughly the same time as the
science target when aiming for precise photometry in the J-band.

Columns 2 and 3 of Table 7 show the fractional contributions
of $\kappa_{Ray}$ and $\kappa_{mol}$ to the total vertical atmospheric extinction.
Molecular absorption dominates the absorption in $J$ (82%), $H$
(88%) and $K_s$ (98%). Molecular absorption and Rayleigh scat-
tering contribute almost equally to the absorption observed in $J_s$.
This is due to the design of the ISAAC $J$ filter which is narrower
than $J$ and avoids the strong atmospheric absorption lines at the
end of $J$-band.

6. Determination of the color terms

According to Amico et al. (2002), the $J$, $H$ and $K_s$ filters of
ISAAC closely match the filters tabulated in Persson et al.
(1998). We therefore expect negligible color terms for these filters.
The $J_s$ filter of ISAAC, on the other hand, is significantly
different to $J$, so we expect a significant color term for $J_s$.

We observed 8 bright red stars from Persson et al. (1998)
with ISAAC in $J, J_s, H$ and $K_s$ under photometric conditions
(see Table 8). Each star has been observed over a grid of four po-
positions (one for each quadrant of the detector) with a windowed
detector and short integrations ($<1$ s) to avoid saturation. The
integrations were shorter than the minimum integration time re-
quired for full readout of the array, so only a subarray of the
detector was read out.

We integrated the flux in apertures of fixed size to derive
instrumental magnitudes for each star. The final instrumental
magnitude associated to the star ($m_{IS}$) is the weighted average
of the four instrumental magnitudes corrected using the atmo-
spheric extinction coefficients determined in Sect. 4 (see Col. 2
in Table 4).

In Fig. 7 we plot ($M_{cat} - m_{IS}$) against ($J - K_s$), and fit for the
slope $C_m$. An arbitrary constant vertical offset has been applied
to the points in each of the graphs.

Table 8 lists ($M_{cat} - m_{IS}$), for $J, J_s, H$ and $K_s$ and the color
($J - K_s$). The slopes, $C_m$, are also reported.

As expected, $C_m$ does not differ from 0 for $J, H$ or $K_s$, while
$C_m = 0.020 \pm 0.009$ for $J_s$.

7. Conclusions

In this Research Note, we have characterized the extinction prop-
erties in the NIR at the Paranal Observatory (Chile). We have
used standard stars observed with ISAAC in $J, J_s, H$, and $K_s$
during photometric and clear nights at the Very Large Telescope
UT1 between 2000 and 2004.

For each star we calculated the zeropoint uncorrected for
extinction using the ISAAC Pipeline. A correction is then per-
formed on the whole dataset in order to eliminate the affects on
the zeropoints due to technical events (such as recoatings of the
primary mirror and ISAAC interventions).

We used two different methods to derive extinction co-
efficients. In the first method, we account for the variation in the
ZPs with the PWV by rescaling the zeropoints to the median
PWV (2.3 mm) measured at Paranal between 2001 and 2005. We
then fit a linear relation to Bouguer curves to determine the
extinction coefficients. We have obtained $\kappa_J = 0.072 \pm 0.040$,
$\kappa_J = 0.048 \pm 0.019$, $\kappa_H = 0.034 \pm 0.015$ and $\kappa_K = 0.043 \pm
0.013$ mag airmass$^{-1}$. In the second method, we have calcu-
lated $\kappa$ considering the zeropoints in three different PWV ranges:
PWV $\sim 0.5–2$ mm, PWV $\sim 2–4$ mm, and PWV $\sim 4–7$ mm. As ex-
pected, the extinction coefficient in $J$ is more sensitive to the
amount PWV than the extinction coefficients of other filters,
increasing by $-0.05$ mag airmass$^{-1}$ between lower and upper
ranges for the PWV. For comparison the coefficients for $J_s$ and
$H$ increase by $-0.03$ mag airmass$^{-1}$ and $-0.02$ mag airmass$^{-1}$,
respectively, while there is negligible change for $K_s$.

Using a theoretical approach, we have found that molecular
absorption contributes most to the total absorption in $J$ (82%), $H$
(88%) and $K_s$ (98%), while Rayleigh scattering contributes most
to the total absorption in the $J_s$-band.

We have calculated the color terms using 8 bright stars ob-
erved in photometric conditions. We have found negligible
color terms in $J, H$ and $K_s$ and a non-negligible color term in
$J_s (0.020 \pm 0.009)$.

Acknowledgements. The authors acknowledge the reviewer for the useful comments. The authors also acknowledge Poshak Gandhi of Institute of Astronomy (University of Cambridge) for the useful codes used in the preliminary part of the study and Marc Sarazin of ESO for the useful comments on the GOES satellite data.

References

Allen, C. W. 2000, Allen’s Astrophysical Quantities, 4th edn., ed. A. N. Cox
Amico, P., Cuby, J. G., Devillard, N., Jung, Y., & Lidman, C. 2002, ISAAC Data
Reduction Guide 1.5, ESO Very Large Telescope
Burki, G., Rufener, F., Burnet, M., et al. 1995, A&AS, 112, 383
Erasmus, A., & Peterson, R. 1997, PASP, 109, 208
Erasmus, A., & Sarazin, M. 2000, SPIE Proc., 4168, 317
Erasmus, A., & Sarazin, M. 2002, in Astronomical Site Evaluation in the Visible
and Radio Range, ed. J. Vernin, Z. Benkhalidoun, & C. Muñoz-Tuñón, ASP
Conf. Proc., 266, 310
Frogel, J. A. 1998, PASP, 110, 200
Hayes, D. S., & Latham, D. W. 1975, ApJ, 197, 593
ISAAC User Manual 2009, Issue 2, ESO Very Large Telescope, http://www.eso.
eso.org/sci/facilities/paranal/instruments/isaac/doc/
Johnson, H. L. 1965, Comm. Lunar Planet. Lab. 3, 67
Lombardi, G., Zitelli, V., Ortolani, S., Fedini, M., & Ghedina, A. 2008, A&A, 483,
651
Lombardi, G., Zitelli, V., & Ortolani, S. 2009, MNRAS, 399, 783
Manduca, A., & Bell R. A. 1979, PASP, 91, 848
Penndorf, R. 1957, J. Opt. Soc. Amer., 47, 176
Persson, S. E., Murphy, D. C., Krezezinski W., Roth M., & Rieke, M. J. 1998,
ApJ, 116, 2475
Rothman, L. S., Gordon I. E., A. Barbe, A., et al. 2009, J. Quant. Spectr. Radiat.
Trans., 110, 533
Rufener, F. 1986, A&A, 165, 275
Soden, B. J., & Bretherton, F. P. 1993, J. Geophys. Res., 98(D9), 16669