(A) Radionuclides in Meteorites:

The production of cosmogenic nuclides depend sensitively on the size and shielding depth of meteorites. The production due to SCR protons is confined to first ≈ 20 g cm⁻² of depth and in deeper regions GCR protons and their secondaries (viz. neutrons, protons and charged π mesons etc.) dominate. Due to the atmospheric ablation suffered by meteorites, the layers containing SCR records are usually lost. Only in a few rare cases of ablation, near surface regions can survive the atmospheric transit (Bhandari et al. 1980).

The nuclide production rate at any depth depends on (i) the target element concentration, (ii) the reaction excitation functions, and (iii) the flux and energy spectrum of nuclear active particles. There are three main approaches of calculation of production rates: (i) thick target bombardment calculations (Kohman and Bender 1967, Trivedi and Gai 1973), (ii) Monte-carlo simulation of intranuclear evaporation-cascade in thick target irradiations (Armstrong and Alsmiller 1971, and Van Ginniken and Turkevich 1970), and (iii) analytical method using thin target excitation functions and flux and energy spectrum of primaries and secondaries. This last method has the advantage in that it allows for more and more refinement as and when improved and new cross-section data become available. An analytical method of calculating the spectra of primary and secondary
nucleonic flux was first attempted by Ebert and Wanke (1957) which was later improved by Lavrukhina et al. (1969). Reedy and Arnold (1972) developed an analytical model to calculate depth profiles of radionuclides in the Moon, based on an approach similar to that of Arnold et al. (1961). This model requires a priori knowledge of the flux and shape of the energy spectrum of the nuclear active particles and the reaction excitation functions. The production rate at depth \( X \) in a body of effective preatmospheric radius \( R_E \) is given by equation I.4 (Chapter-I). In Reedy-Arnold model the energy spectrum above \( E \sim 100 \text{ MeV} \) is assumed to be of the form

\[
\frac{dj}{dE}(X, R_E) = K(a + E)^{-2.5}
\tag{IV.1}
\]

and in the energy range of \( 2.5 \leq E < 100 \text{ MeV} \),

\[
\frac{dj}{dE}(X, R_E) = K(a + 100)^{-2.5} \{ M(E) - (a - 50) \delta(E) \} \tag{IV.2}
\]

where \( M(E) = 94E^{-1} + 603E^{-2} - 300E^{-3} \)

and \( \delta(E) = 0.3E^{-1.26} - 0.00091 \) \( \tag{IV.3} \)

In \( 0.5 \leq E \leq 2.5 \text{ MeV} \), the spectrum is assumed to be

\[
\frac{dj}{dE}(X, R_E) = K(a + 100)^{-2.5} \{ 115 - (a - 50) \times 0.094 \}
\times \{ 1.3175 + 0.5E - 0.25E^2 \} \tag{IV.4}
\]
In above equations, \( J \), \( K \) and \( \alpha \) are functions of \( X \) and \( R_E \). In general Reedy-Arnold model predicts the depth variation in agreement with the measured depth profiles of some isotopes in the Moon (Kohl 1975, Finkel 1972), but there are disagreements between the measured and calculated production rates for other isotopes. This discrepancy may be due to inaccurate and scanty cross-section data available.

If \( F_0 \) is the integral proton flux above 1 GeV in free space and \( F_G \) is the integral nucleonic flux (>1 GeV) at geometrical depth \( X \) in a meteoroid body of effective radius \( R_E \), then we have

\[
F_G(X, R_E) = \sum \int_0^{\pi} \int_0^{2\pi} F_0 \exp\left(-\frac{X}{\lambda_p}\right) + aF_0 \exp\left(-\frac{X}{\lambda_\alpha}\right)
+ b \frac{F_0}{d} \left[ \exp\left(-\frac{X}{\lambda_p}\right) - \exp\left(-\frac{X}{\lambda_\alpha}\right) \right] \left( \frac{1}{d} - \frac{1}{\lambda_p} \right) \sin \theta d \theta
\]

where \( \lambda_p \), \( \lambda_\alpha \), \( a \), \( b \) and \( d \) are constants taken from Reedy and Arnold (1972),

\( \theta \) is zenith angle,

\( \phi \) is azimuthal angle, and

\( r(X, R_E, \theta) \) = distance along zenith angle \( \theta \) of a point at geometrical depth \( X \) and is given by (Bhattacharya et al. 1972),
\[ r(X, R_E, \theta) = -(R_E - X) \cos \theta + \left( R_E^2 \cos^2 \theta + 2 R_E X \sin^2 \theta - X^2 \sin \theta \right)^{1/2} \] ...... (IV.6)

The depth variation of the spectral shape parameter was obtained by Bhattacharya et al. (1980) from the experimental depth profiles of $^{53}$Mn in meteorites of different sizes. Using the production excitation function of Gensho et al. (1978) for $^{53}$Mn production from Fe, the free space GCR integral proton flux of $1.7 \text{ protons/(cm}^2 \cdot \text{sec} \cdot \text{4 nsr)}$ and absorption and interaction parameters of Reedy and Arnold (1972), they calculated the values of $\alpha$ for 6.5, 9, 15 and 25 cm size meteorites. For large meteorites this value is not available.

Here we derive the depth profile of spectral shape parameter from the measured $^{26}$Al depth profile in a 50 cm radius meteoroid Dhajala. Using these deduced $\alpha$ values, the expected production depth profiles of other radionuclides viz. $^{10}$Be and $^{22}$Na are calculated and compared with experimental profiles.

1. The $^{26}$Al depth profile and spectral shape parameters:

The depth profile of $^{26}$Al in Dhajala has been described in Chapter-III and is shown in Fig.III.3. The best fit depth profile is used to deduce the values of spectral shape parameter, $\alpha$.

The $^{26}$Al is mainly produced from target elements Al and Si due to GCR particles. The production reactions are (Table-I.1).
### TABLE IV.1

Calculated characteristics of the nucleonic spectra in a 50 cm body

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Spectral shape parameter (MeV)</th>
<th>Normalising constant, K particles/</th>
<th>$J_G (&gt; 1 \text{ GeV})$ particles/(cm²·sec·4πsr)</th>
<th>$J_G (&gt; 10 \text{ MeV})$ particles/(cm²·4πsr·MeV⁻³/²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>372</td>
<td>87523</td>
<td>1.179</td>
<td>10.601</td>
</tr>
<tr>
<td>10</td>
<td>310</td>
<td>73095</td>
<td>1.057</td>
<td>12.114</td>
</tr>
<tr>
<td>15</td>
<td>272</td>
<td>63846</td>
<td>0.967</td>
<td>13.169</td>
</tr>
<tr>
<td>20</td>
<td>260</td>
<td>58310</td>
<td>0.895</td>
<td>12.953</td>
</tr>
<tr>
<td>25</td>
<td>252</td>
<td>54189</td>
<td>0.841</td>
<td>12.667</td>
</tr>
<tr>
<td>30</td>
<td>250</td>
<td>51333</td>
<td>0.793</td>
<td>12.156</td>
</tr>
<tr>
<td>35</td>
<td>247</td>
<td>49077</td>
<td>0.767</td>
<td>11.929</td>
</tr>
<tr>
<td>40</td>
<td>243</td>
<td>47519</td>
<td>0.744</td>
<td>11.781</td>
</tr>
<tr>
<td>50</td>
<td>240</td>
<td>46275</td>
<td>0.729</td>
<td>11.704</td>
</tr>
</tbody>
</table>
H Chondrites
($R_E =$ Effective Radius)

Present work

--- Bhattacharya et al. 1980

--- Reedy & Arnold, 1972

--- B = 6.5 cm

--- $R_E = 9.0$

--- $R_E = 15.0$

--- $R_E = 25.0$

--- $R_E = 50.0$

--- $R_E = \infty$

**Fig. IV.1** Spectral shape parameter as a function of depth in 6.5, 9.0, 15.0, 25 cm (Bhattacharya et al. 1980), in 50 cm chondrites (present work) and in Moon (Reedy and Arnold, 1972).
$^{26}\text{Mg}(p,n)^{26}\text{Al}$, \\
$^{27}\text{Al}(p,p\alpha)$ and $^{27}\text{Al}(n, 2n)$, \\
and, $^{28}\text{Si}(p,\alpha p)$ and $^{28}\text{Si}(n, \alpha p\alpha)$.

Mg contribution is found to be negligible, and other target elements do not contribute more than 2%.

The reaction cross-sections of production are available for the energy range 25-52 MeV (Furukawa et al. 1971) and at 600 MeV and 24 GeV (Regnier 1973). These cross-sections are known within ±10% uncertainty. The contribution due to $^{26}\text{Mg}$ is very small and is neglected. The target element abundances are Al:1.15% and Si:17% by wt in Dhajala (H3) chondrite.

In Table-IV.1, the results of the calculations are presented. The best fit $\alpha$ values, deduced $K$ values and flux above energy 1 GeV and 10 MeV are also tabulated. The exposure age of 6.3 Myr based on cosmogenic $^{21}\text{Ne}$ and $^{38}\text{Ar}$ was adopted for calculating the production rates (Gopalan et al. 1978). The GCR flux above 1 GeV decreases with depth whereas the flux > 10 MeV first increases with depth upto ~15 cm (due to secondary production) and then decreases.

The best fit $\alpha$ values deduced are shown in Fig.IV.1. For comparison, the $\alpha$ values for $R_{\varepsilon} < 25$ cm chondrites (Bhattacharya et al. 1980) and for Moon (Reedy and Arnold 1972) are also shown.
(2) \( ^{22}\text{Na} \) depth profile and GCR modulation during solar cycle 20:

The experimental depth profile of \( ^{22}\text{Na} \) is described in Chapter-III and is shown in Fig.III.4. Whereas the shape of the profile is similar to the calculated profile, the absolute values are about 35% higher than the calculations. Since the calculated values are based on long-term average GCR flux of 1.7 protons/(cm\(^2\).sec.4\(^\text{sr.} \times 1 \text{ GeV}) and Dhajala fell at the time of solar minimum, the higher \( ^{22}\text{Na} \) activity may be due to higher GCR fluxes during the past decade before the fall. The excitation functions for \( ^{22}\text{Na} \) production from target elements Mg, Al, Si and Na are given in Fig.V.1(c).

This 2.56 yr half-life \( ^{22}\text{Na} \) is produced mainly during the decade before the fall of the Dhajala chondrite in 1976, which covered the entire solar cycle 20 (1965-1976). The GCR flux in the interplanetary medium is modulated due to solar activity and before we calculate the effect of solar modulation, it is essential to know the GCR fluxes during the solar cycle 20.

GCR fluxes during Solar Cycle 20:

For the calculation of modulation effect on \( ^{22}\text{Na} \) production the available measurements of GCR spectra (Bedijn et al.1973, McKibben 1977, Hsieh et al.(1971), Garcia-Munoz et al (1975a, b, c and 1977) over entire
Interstellar (Garcia-Munoz et al., 1975c)

![Graph showing quiet time GCR spectra at 1 A.U. during Solar Cycle 20 and 1973 local interstellar GCR spectrum.](image)

**Fig IV.2** Quiet time GCR spectra at 1 A.U. during Solar Cycle 20 and 1973 local interstellar GCR spectrum.
period of solar cycle 20 are used. The measurements at 
\( \gtrsim 1 \) GeV are limited but there are good measurements
available in \( \sim 100 \) MeV to \( \sim 1000 \) MeV region during solar quiet times for all the years covering solar cycle 20.
These quiet time fluxes are taken to be the representative
of the annual average GCR fluxes at 1 A.U. In view of the
hysteresis effect observed at low energies, particularly
during solar sunspot minimum (Van Hollebeke et al., 1972,
Burger and Swanenberg, 1973), only the high energy
measurements are used for extrapolation to determine the
GCR spectra at \( \gtrsim 1 \) GeV energies. This extrapolation is
guided by the available high energy measurements, models
of GCR modulation, the local GCR interstellar spectrum and
the interplanetary spectrum of 1973 (Garcia-Munoz et al., 1975).
The available measurements of GCR spectra based on literature
cited above are shown in Fig. IV.2. The spectrum beyond 20
GeV for all the years is assumed to have the spectral form
given by (Wolfendale 1975):

\[
\frac{dJ(E)}{dE} = k E^{-2.65} \quad \cdots \quad (IV.5)
\]

The calculated integral proton flux above 1 GeV
are given in Table-IV.2. The errors in the measured
fluxes are of the order of 5 to 10% at 1 GeV, and since
the integral proton flux depends mainly on GCR flux at 1 GeV
the errors in the flux estimates are of the same order. The
annual average GCR flux varied between 1.32 protons/
\( (cm^2 \cdot sec \cdot 4\pi \ sr. >1 \) GeV) in 1970 to 2.36 protons during
1976, with average of 1.9±0.1 protons/\( (cm^2 \cdot sec \cdot 4\pi \ sr. >1 \) GeV).
TABLE IV.2

Computed GCR proton fluxes, $J_G( > 1 \text{ GeV})$ at 1 A.U. during Solar Cycle 20

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual mean $4 \pi$ integral proton flux $J_G( &gt; 1 \text{ GeV})$ (protons/cm$^2$.sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>2.23</td>
</tr>
<tr>
<td>1966b</td>
<td>1.97</td>
</tr>
<tr>
<td>1967a</td>
<td>1.57</td>
</tr>
<tr>
<td>1968b</td>
<td>1.62</td>
</tr>
<tr>
<td>1969a,c</td>
<td>1.48</td>
</tr>
<tr>
<td>1970c</td>
<td>1.32</td>
</tr>
<tr>
<td>1971c</td>
<td>1.66</td>
</tr>
<tr>
<td>1972c</td>
<td>2.04</td>
</tr>
<tr>
<td>1973c</td>
<td>1.95</td>
</tr>
<tr>
<td>1974c,e</td>
<td>2.06</td>
</tr>
<tr>
<td>1975f</td>
<td>2.23</td>
</tr>
<tr>
<td>1976o</td>
<td>2.36</td>
</tr>
</tbody>
</table>

Solar cycle 20 average proton flux $J_G( > 1 \text{ GeV}) = 1.9 \pm 0.1$ Protons/(cm$^2$.sec.4 $\pi$ sr)

a) Hsieh et al. (1971)
b) Bedijn et al. (1973)
c) Garcia-Munoz et al. (1975b)
d) McKibben (1977)
e) Garcia-Munoz et al. (1977)
f) Garcia-Munoz et al. (1975a)