Possible Effects of Terrestrial Magnetic Field Polarity Transitions on Aquatic Ecosystems

EcoMag

Research Proposal
submitted to the
Deutsche Forschungsgemeinschaft

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Application for a New Project (Neuantrag)

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1.2 Topic (Thema)

Possible effects of geomagnetic polarity transitions on the biosphere

1.3 Code name (Kennwort)

EcoMag

1.4 Scientific discipline and field of work (Fachgebiet und Arbeitsrichtung

Geophysics, Geomagnetism, Environmental Geology, Geoecology, Biology

1.5 Scheduled total duration (Voraussichtliche Gesamtdauer)

Three years; July 1, 2005 – June 30, 2008

1.6 Application period (Antragszeitraum)

Two years; July 1, 2005 – June 30, 2007

1.7 Start of funding period (Förderbeginn)

July 1, 2005

1.8 Summary (Zusammenfassung)

The Earth possesses a global magnetic field for at least 3.5 billion years. This geomagnetic field exhibits major temporal variations with the most dramatic one being a polarity transition. As during such a transition the surface field almost collapses the question of possible effects of this collapse is a most important one. If energetic particles have much better access to the atmosphere during a polarity transition, this may cause an increased nitric oxygen level in the middle atmosphere with a resulting decrease of the ozone column density and a corresponding increase in the surface UV-B radiation. In order to better understand the coupled magnetosphere-ionosphere-atmosphere-biosphere system we propose to develop detailed models of the effect of such a UV-B level increase on selected aquatic ecosystems. By using models describing the atmospheric nitric oxygen increase and the associated UV-B increase during polarity transitions, a bio-optical and phytoplankton model as well as an evolutionary model we want to test (i) the non-

linear response of the biosphere on geomagnetic field changes and its delay times, (ii) the sensitivity of different species of the aquatic ecosystem to polarity transition induced UV-B radiation changes and possible evolutionary effects. Another aim of the proposed studies is the identification of proxies that show evidence for the proposed reaction sequence of the magnetosphere-ionosphere-atmosphere-biosphere system on polarity transitions.

2 State of the art and preliminary work (Stand der Forschung und eigene Vorarbeiten)

2.1 State of the art (Stand der Forschung)

At least since 3.5 billion years planet Earth possesses a global magnetic field which origin is a thermo-gravitationally driven dynamo in the outer core of the Earth. Paleomagnetic studies reveal that this geomagnetic field undergoes large secular variations of its topology as well as strength. The most dramatic change of the geomagnetic field is a polarity transition in which the main component of the field, the dipole component, changes polarity. Such a polarity transition takes about 5,000 years with the surface magnetic field decreasing to about 10% of its normal magnitude [e.g. Merrill and McFadden, 1999]. Transitions are not occurring on a regular, periodic time scale, but are more chaotic events. The last known transition, the Matuyama-Brunhes transition, occurred about 780,000 years ago. Counting the transitions during the last 10 Million years gives one a transition time scale of about 200,000 years. This and the observation that the dipole moment is currently decaying at a fast rate let speculations that the geomagnetic field is approaching another polarity transitions [e.g. Glassmeier, 2003 and references therein]. However, paleomagnetic studies also indicate that the geomagnetic field was much stronger some 4,000 years ago, reaching dipole moments a factor 1.5 larger than today. This can also indicate that the current field is merely trying to reach its nominal strength rather than approaching a transition [e.g. Tauxe, 1993].

The current debate about the future of the geomagnetic field raises the question which effects of a polarity transition and other secular variations might have existed on Earth, that is in which way the magnetosphere-ionosphere-atmosphere-biosphere (MIAB) system is reacting on a polarity transition. A commonly accepted hypothesis is that Earth without any significant global magnetic field will suffer from the severe particle bombardment caused by cosmic and solar particle radiation. This led to the interpretation of the geomagnetic field representing a shield against this radiation. If this shield collapses major impacts on the biosphere are expected. The correlation between secular variations of the geomagnetic field intensity and enhanced cosmic-ray production of ^{10}Be or ^{36}Cl is well established [e.g. McHargue et al., 2000; Baumgartner et al., 1998] and indicates that the geomagnetic field is at least strongly moderating the access of energetic particles into the atmosphere. Despite several studies searching, for example, a correlation between polarity transitions and faunal extinctions [e.g. Hays, 1971; Raup, 1985] there is no clear evidence and the question whether polarity transitions have a major effect on the biosphere and via what mechanisms is still open.

A possible link between the geodynamo and the biosphere is via the atmosphere. For example, Tinsley and Deen [1991] speculate about a connection via electro-freezing of super cooled water in the troposphere. Another possible link is suggested via energetic particle induced NO_X and HO_X increases in the middle atmosphere, subsequent vertical transport of these molecules down to the stratosphere where a clear decrease of the ozone column density should result. This in turn implies a significantly increased level of UV-B radiation with possible effects on the biosphere. This chain of interactions is well established by recent observations during solar proton events (SPE) and their effects on the atmosphere [e.g. Crutzen et al., 1975; Jackman et al., 2001]. During a normal SPE these atmospheric effects are minor, yet detectable. A long-duration decrease of the stratospheric ozone, however, and an increase of the UV-B is not expected due to such normal SPEs.

The consequences of a tropospheric UV-B increase are the topic of many studies. Since many decades the total ozone column is measured continuously at different locations on the Earth and in orbit. The results indicate a current latitude dependent decrease of the stratospheric ozone with major effects observed in the polar region, that is in the so-called ozone hole [e.g. Solomon, 1988; Staehelin et al., 2001]. A decrease in the stratospheric ozone is expected to be accompanied by an increase in tropospheric UV radiation as the stratospheric ozone constitutes a filter against harmful UV-B radiation. Thus a reduction of total ozone causes an increase in the terrestrial erythemal irradiation dose [e.g. Casale, 2000].

However, more detailed studies by Sinnhuber et al. [2003] and Schröder et al. [2005] indicate a major global reaction of the atmosphere on heavy energetic particle bombardment during periods of low-geomagnetic field and assuming strong SPEs. A large natural ozone hole around the northern rotation pole during boreal winter was modelled assuming zero geomagnetic field. The ozone column density was depleted by up to 50% accompanied by a drastic increase of the UV radiation at the ground. It is this increase of radiation which will have a major effect on members of the biosystem.

The obvious question is what are the consequences of this decrease on the biosphere. As most of the Earth surface is covered by the oceans this question can be focused on the effect of aquatic systems to increased UV-B stress. All aquatic organisms are susceptible to UV-B. It has the potential to cause different effects, including alteration in the structure of proteins, DNA and other biologically relevant molecules, chronic depression of key physiological processes, and acute physiological stress.

Many photosynthetic organisms, which are exposed to visible and UV radiation in their natural environment, have developed strategies to minimize damage from UV exposure. Examples for such mechanisms are: repair of DNA-damage by photo reactivation and excision repair [e.g. Britt, 1995], accumulation of carotenoids and detoxifying enzymes or radical quenchers and antioxidants that provide protection by scavenging harmful radicals or oxygen species [e.g. Mittler, 1991]. A further mechanism is to synthesize photoprotective compounds, e.g. scytonemin and mycosporine-like amino acids (MAAs) [e.g. Sinha and Häder, 2002].

Aquatic organisms such as phytoplankton or algae can synthesize compounds that directly or indirectly absorb UV energy. MAAs are one class of these UV-absorbing compounds, with absorption maxima between 309 to 360 nm. MAAs have been found in phytoplankton and benthic cyan bacteria, with MAA concentrations in phytoplankton declining with depth. Cyan bacteria can also synthesize scytonemin, which has a maximum absorption at 370 nm (e.g. Garcia-Pichel and Castenholz 1991). A third group of protective compounds employed by algae are the carotenoids, which do not directly absorb UV but are quenchers of radical oxygen species. All this indicates that members of aquatic ecosystems have a variety of possibilities to react on increased UV-B irradiation with the actual consequences depending on the actual conditions in their ecosystem.

The production of compounds directly or indirectly absorbing UV-B radiation that preserve over time provides a proxy for the reconstruction of past solar UV-B [e.g. Rozema, 2002] and thus opens a possibility to correlate the paleomagnetic field record with any energetic particle induced decrease of the ozone column density. However, though the dilution of stratospheric ozone and the related increase of UV-B radiation on the surface is generally confirmed [Madronich, 1992; Kerr, 1993] there is not much information about the occurrence of past analogous events. For this reason it is important to link the UV-B with results of fossil record examinations and furthermore to create a model that predicts the effects of increased UV-B on the biosphere. Consequences of enhanced UV-B on especially aquatic ecosystems derived on the basis of already known facts may be generally the (1) loss of biomass [e.g. Leavitt et al. 2003], (2) changes in species composition, (3) decrease in availability of nitrogen compounds and (4) reduced sink capacity for atmospheric carbon dioxide [e.g. Häder, 2000]. Though major consequences of increased UV-B radiation on aquatic ecosystems are thus expected the question remains whether UV-penetration is directly controlled by the atmospheric ozone column density or whether dissolved organic matter (DOM) influenced by major environmental changes controls the UV-penetration. Studies by Pienitz and Vincent [2000] reveal that DOM probably plays the more dominating role.

If indeed the magnetosphere and the atmosphere are more accessible to energetic particles during polarity transitions, and if this leads to natural ozone holes causing increased UV-B radiation stress at the Earth surface then major impacts on aquatic organisms and ecosystem are expected. This scenario could be tested by stratigraphic evidence. In 1967 paleomagnetic polarity changes have been detected in nine deep-sea sedimentary cores from the Pacific-Antarctic Basin where in an extinction horizon of radiolarian assemblages closely correlates with a polarity change [Watkins, 1967]. In a further detailed study of 28 deep-sea piston cores that cover the last 2.5 m.y. eight species of radiolaria became extinct (Fig. 1; Hayes, 1971). Rozema [2002] presented evidence for enhanced solar UV-B inducing increased UV-B absorbance of sporopollenin in pollen and spores of mosses, which may be preserved in the fossil record. The use of UV-B absorbing polyphenolics in pollen as a proxy of solar UV-B may allow reconstruction of historical UV-B levels. The comparison with sedimentary data of reversals and fossil pollen or spores may be an appropriate proxy for the possibility that increased cosmic radiation at the time of a reversal may affect organisms. Sediments from aquatic systems that include UV-sensitive proxies may provide a test for any past UV climate (Rozema et al., 2002).

Previous studies thus allow to formulate the hypothesis that during a geomagnetic polarity transition energetic particle cause a significant decrease of the atmospheric ozone coupled with a clear increase of the surface UV-B radiation. As UV-B radiation is known to have major effects on, for example, aquatic ecosystems polarity transitions may effect the biosphere via the outlined processes. However, the question remains how important this influence is with respect to other controlling factors such as the production of DOM or solar activity [e.g. Roezema et al., 2002] and to what extend the geomagnetic field influence can be quantified and separated from the other controlling factors.

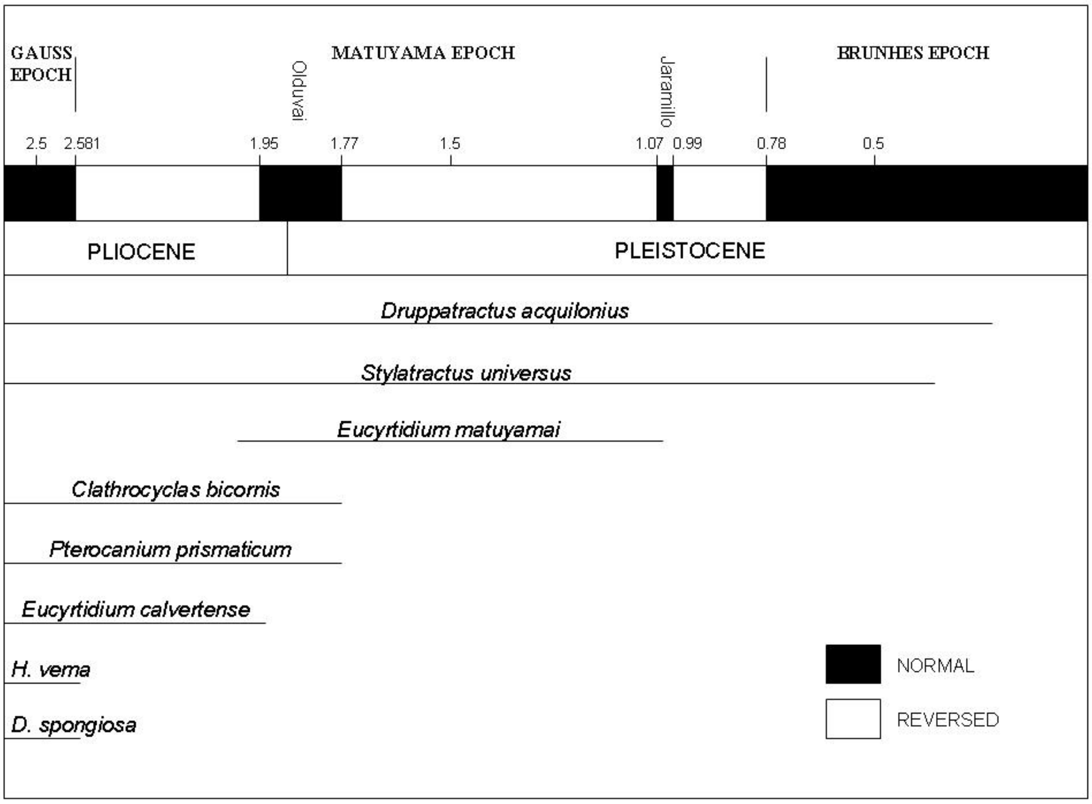

Fig. 1 Radiolaria extinction associated with paleomagnetic epochs and events (after Hays, 1971).

2.2 Preliminary work (Eigene Vorarbeiten)

The topic of the proposed research is a very interdisciplinary one. Thus three applicants with different fields of expertise are jointly proposing this study. All three are working at the same university in the same faculty. This guarantees a very high level of cooperative research and has stimulated this very interdisciplinary research proposal.

The applicants are experienced in modelling and analysing the magnetosphere-ionosphere-atmosphere-biosphere system (see also the attached list of publications). Karl-Heinz Glaßmeier has extensive experience in the field of magnetospheric and ionospheric physics [e.g. Vogt and Glassmeier, 2000; Vogt and Glassmeier, 2001; Glassmeier et al., 2004; Stadelmann et al., 2005]. These studies tackle the problem of magnetospheric dynamics during a polarity transition and the impact of energetic particles on the atmosphere. Results from these studies are currently used to update the work by Sinnhuber et al. [2003] with respect to more realistic magnetic field configurations. Tools under development at the Technical University of Braunschweig, the University of Osnabrück, and the University of Bremen will allow a detailed modelling of the magnetosphere-ionosphere-atmosphere part of MIAB for typical reversal conditions.

Modelling complex ecosystems is a speciality of Otto Richter [e.g. Richter, 1985; Richter and Söndgerath, 1990]. His current work is related to flow models of genetic information in ecosystems [Richter and Seppelt, 2002 and 2004], population dynamics modelling [e.g. Apel et al., 2003], or questions of the global carbon dioxide cycle [e.g. Hiete et al., 2001]. Based on this experience first models have been designed to study the increase of UV-B and the associated phytoplancton dynamics. These studies show the feasibility of our approach.

In her research Antje Schwalb uses a combination of micropaleontology, sedimentology and stable isotope geochemistry to reconstruct environmental dynamics and climate [e.g. Schwalb et al., 2003]. She has worked with lake systems from different climate sensitive areas ranging from the Alpine region of Central Europe [e.g. Schwalb et al., 1998], the north-central USA [e.g. Schwalb et al., 2002a], the Chilean Altiplano [e.g. Valero-Garcés et al., 2003] to the Patagonian Steppe [Schwalb et al., 2002b, Markgraf et al., 2003]. One of her main interests is the response of fossil species assemblages to past environmental and climate change. She will thus provide expertise in paleoecology and paleoclimate to the project.

The PhD student, Petra Moebus, for whom funds are requested here, holds a diploma in Geoecology and is highly skilled for the kind of research proposed. Since October 1, 2004 Petra Moebus is already working on the subject, supported by internal funds of the Institute of Geophysics and extraterrestrial Physics of the TU Braunschweig. Since that time a very thorough literature search has been conducted and first contacts with other international working groups have been established.

3 Goals and work schedule (Ziele und Arbeitsprogramm)

3.1 Goals (Ziele)

The scientific aim of the proposed study is to develop a model which allows to study in more detail certain aspects of the magnetosphere-ionosphere-atmosphere-biosphere system during a geomagnetic polarity transition. In particular, we aim to model the reaction of the aquatic biosphere on increased UV-B radiation that may occur during a polarity transition due to increased access of energetic particles into the atmosphere. The conceptual model of EcoMag is outlined in Fig. 2.

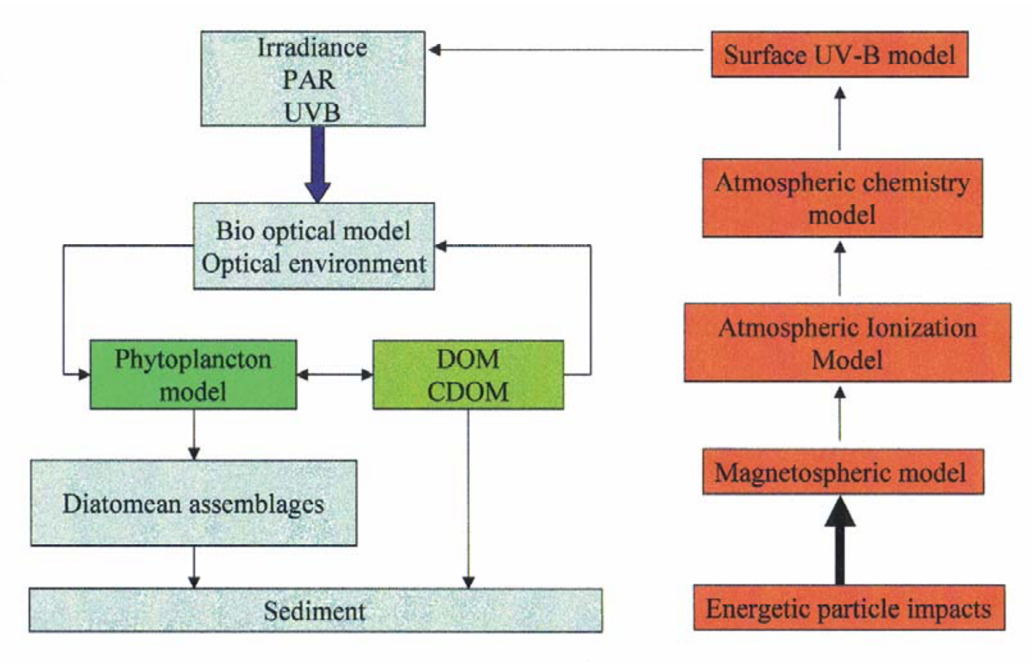

Figure 2. The EcoMag conceptual model

Two sets of state variables are important for this model. The first set is given by the flux of impacting energetic particles and its variation in time, the structure of the geomagnetic field during a polarity transition as represented by the spherical harmonic coefficients of the field, and general atmospheric conditions. The existing magnetosphere-ionosphere-atmosphere model accessible to us [Stadelmann, 2005; Schröder et al., 2005; Sinnhuber et al; 2003] allows to determine surface estimates of photosynthetically active radiation (PAR) and the UV-B flux. The second set of state variables to be used in a bio-optical model are the PAR and UV-B radiation as determined from the first chain of models as well as phytoplankton density and the optical environment and formation of the benthic community.

The process chain **“Increased particle impact to increase of the surface UV-B**” (see the right part of Fig. 1) is already well covered by models accessible to us. For various scenarios of particle fluxes such as solar proton events with different strength, repetition period etc. and of the magnetic field topology shortly before, during, and after a polarity transition we aim at determining the modification of the surface UV-B radiation at the Earth surface.

The development of the process chain “**Increase of UV-B and associated diatom assemblages as seen in sedimentary structures**” (see the left part of Fig. 1) has already been started. Of importance is here the PAR in the wavelength range 400-700 nm as it is an important factor for the formation of chlorophyll and associated herbal growth. In the UV-B range radiation with a wavelength of 280-330 nm matters and causes negative effects on organisms such as photo inhibition or DNA damage.

Phytoplankton density strongly depends on PAR and nutrient content. It has a major effect on the optical environment as it produces DOM and coloured dissolved organic matter (CDAM) which are the characteristic parameters for the optical environment of the system to be modelled. High concentrations of CDOM and DOM inhibit the penetration of UV-B. It is the UV-B-sensitivity of the benthic community, which finally determines the effects of increased UV-B. The following models need to be developed or extended:

The energetic particle effect model

The model allows to study effects of increased energetic particle impact to the atmosphere. Components of the model are

- energetic particle spectrum
- energetic particle flux pattern
- magnetic field topology during a polarity transition, and
- atmospheric structure

The processes comprise

- structure of the paleomagnetosphere
- propagation of energetic particles in the magnetosphere
- ionization of the atmosphere,
- ion chemistry and HO_x as well as NO_x production,
- ozone density depletion, and
- UV-B flux variations

The forcings are

- energetic particles

This model will be based on several documented polarity transitions such as the Matuyama-Brunhes transition. Global distributions of particle impact regions will be determined together with their associated UV-B surface distributions. An existing model needs to be extended. For polarity transitions of the very past a model of plate motions needs to be combined with the modeled surface UV-B radiation.

The population model

The model will be formulated in terms of partial differential equations for algal population dynamics and movement in a water column. Components of the model are

- algal density,
- density of coloured organic matter,
- density of detritus and
- radiation levels of PAR and UV-B.

The processes comprise

- photosynthesis,
- photoinhibition,
- passive and active movement,
- production of CDOM,
- absorption of radiation by in-water components.

The forcings are

- radiation
- temperature
- nutrition

The model will be used to study the emergence and stability of spatio-temporal patterns dependent on radiation fluxes and sedimentation patterns of CDOM.

The key species interaction model

There are several algal classes differing with respect to the distribution of pigments, therefore it is to be expected that community structure and spatial distribution is strongly influenced by the radiation environment. We are aware, that modelling a complete food web is not feasible. Therefore, a model system with only few species shall be set up in order to study

- the emergence of community patterns under constant external radiation forcing
- the resilience of community patterns with respect to short and long term UV-B variation

- changes in community patterns provoked by drastic changes in UV-B fluxes during a polar transition

The genetic drift model

Environmental stress accelerates evolutionary processes. Therefore, the population and interaction models will be reformulated in a genetic setting incorporating mutation and fitness parameters such as the production rate of UV mitigating substances. The model structure will hybrid comprising

- stochastic elements for the generation of mutations
- a genetic submodel
- and a deterministic dynamical model for the interactions of populations

With the family of models as outlined above we shall be able to understand in some detail at least one aspect of MIAB interaction. In particular, we are interested to quantify this interaction with respect to its severity, that is we aim at determining a nonlinear transfer function allowing the assessment of cause-effect relations between increased energetic particle influx during a polarity transition and the hypothetical consequences for the biosphere system assumed here. Also, we are interested in the determination of any lag time between a polarity transition and its possible biospheric consequences. The determination of such a lag time is important for any correlative study between paleomagnetic data and biospheric proxidata.

Furthermore, we like to identify possible stratigraphic signatures which can be used as a suitable proxy to verify our hypothesis.

3.2 Work schedule (Arbeitsprogramm)

The following work packages are necessary to conduct the proposed study; the overall project plan is outline in the attached milestone diagram (Fig. 2).

P1: Handling and maintenance of the magnetospheric and particle module
Permanent task

P2: Definition of a suitable geomagnetic polarity transition scenario
1 months

P2: Model calculations for the surface response of the chosen geomagnetic and energetic particle flux scenario
3 months

P3: Development of the bio-optical model
3 months

P4: Development of the phytoplankton model 3 months

P5: Development of the interaction model 6 months

P6: Development of the genetic drift model 6 months

P7:	Integration of the models	2 months
P8:	Global model runs	4 months
P9:	Hypothesis building for possible proxi	2 months
P10:	Final evaluation	6 months

The work packages P1 to P7 define to first proposal period, for which funding is requested here.

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4 Funds (Beantragte Mittel)

4.1 Staff (Personalbedarf)

1 x IIa BAT/2 for 2 years (PhD student Petra Moebus; personal details attached)

This research scientist will be responsible for all aspects of the proposed modelling efforts.

4.2 Scientific instrumentation (Wissenschaftliche Geräte)

None

4.3 Consumables (Verbrauchsmaterial)

None; all necessary consumables will be provided by the Institute of Geophysics and extraterrestrial Physics.

4.4 Travel expenses (Reisen)

Travel support is requested for visits at cooperating institutions in Osnabrück, Bremen, Quebec and to present the research results at international science conferences such as the EGU meeting in Vienna:

Cooperation with Prof. Joachim Vogt (IUB,Bremen)

1 Person one single day trip in 2006 and 2007 each	
	200,00 €

Cooperation with Prof. Notholt and Dr. Sinnhuber (University Bremen)

1 person two five-days trip in 2006 and 2007	
	900,00 €

Cooperation with Prof. Kallenrode (University of Osnabrück)

1 person one five-days trip in 2006	
	450,00 €

Cooperation with Prof. Pienitz (Université Laval, Québec)

1 person one seven-days in 2006	
six days (per diem 100,- €)	700,00 €
Flight costs	814,00 €
Access to airports etc.	100,00 €
	1614,00 €

EGU conference Vienna 2006	
1 person for six days (per diem 106,- €)	636,00 €
Train ticket	280,00 €
	916,00 €

EGU conference Vienna 2007	
1 person for six days (per diem 106,- €)	636,00 €
Train ticket	280,00 €
	———
	916,00 €
Total cost of travel:	4996,00 €

The travel costs are entirely planned for Mrs. Petra Moebus. Other travel costs will be covered by internal TUBS funds.

4.5 Publication costs (Publikationskosten)

Publication costs will be covered by internal funds from the Institute of Geophysics and extraterrestrial Physics of the Technical University of Braunschweig.

4.6 Other costs (Sonstige Kosten)

1 x FEMLAB Single User Licence	3845,40 €

The planned modelling of the consequences of energetic particle accessing the magnetosphere-ionosphere.atmosphere system can be performed using existing software codes running using existing licenses such as IDL or Mathematica. However, the planned modelling of the aquatic ecosystem response on ozone depletion will be done using the FemLab Toolkit, a well-tested software system, already in use at the Institute of Geoecology of the Technical University of Braunschweig. However, the existing licenses are personal user licenses which requires to buy at least one more license for the research scientist of the EcoMag team. Using the FEMLAB software is mandatory for this project due to the fast experience in using this software tool already exists at the Institute of Geoecology.

5 Preconditions for carrying out the project (Voraussetzungen für die Durchführung des Vorhabens)

5.1 Our team (Zusammensetzung der Arbeitsgruppe)

The research team at the Technical University of Braunschweig consists of the following people:

Prof. Dr. Karl-Heinz Glaßmeier	Institute of Geophysics and extraterrestrial Physics
Dipl.-Geoökologin Petra Moebus	Institute of Geophysics and extraterrestrial Physics (salary requested here)
Prof. Dr. Otto Richter	Institute of Geoecology
Prof. Dr. Antje Schwalb	Institute of Environmental Geology

5.2 Cooperation with other scientists (Zusammenarbeit mit anderen Wissenschaftlern)

Cooperation with the following research groups is necessary:

Institute of Environmental Physics, University of Osnabrück
M.B. Kallenrode

Institute of Environmental Physics, University of Bremen
J. Notholt
M. Sinnhuber

Dept. of Physics, International University of Bremen
J. Vogt

Centre d'études nordiques, Université Laval R. Pienitz

These colleagues have expressed their large interest in cooperation and support as stated in the attached letters.

5.3 Foreign contacts and cooperations (Arbeiten im Ausland und Kooperationen mit ausländischen Partnern)

Currently we envisage a closer cooperation with Prof. Reinhard Pienitz, Centre d'études nordiques, Départment de géographie, Université Laval in Quebec. As this project is a very interdisciplinary one we aim at building up further intensive contacts with other research groups in foreign countries in order to find support for the planned activities. Attending meetings such as the EGU meeting is a very suitable opportunity to build up these contacts and cooperations.

5.4 Scientific equipment available (Apparative Ausstattung)

The planned model calculations can be done on existing personal computers and by accessing the supercomputer facility of the state of Lower Saxonia.

5.5 Running costs (Laufende Mittel)

All running costs will be covered by funds from the Institute of Geopyhsics and extraterrestrial Physics of the Technical University of Braunschweig.

5.6 Other requirements (sonstige Vorausetzungen)

None

6 Declarations (Erklärungen)

This proposal has not been submitted to any other research organisation. If we intend to do so we shall immediately inform the Deutsche Forschungsgemeinschaft.

The DFG spokesman at the Technical University of Braunschweig has been informed about this proposal

7 Signatures (Unterschriften)

Braunschweig,

Prof. Dr. Karl-Heinz Glaßmeier   Prof. Dr. Otto Richter   Prof. Dr. Antje Schwalb

8 List of appendages (Verzeichnis der Anlagen)

Curriculum vitae Karl-Heinz Glassmeier
List of publications Karl-Heinz Glassmeier

Curriculum vitae Otto Richter
List of publications Otto Richter

Curriculum vitae Antje Schwalb
List of publications Antje Schwalb

Personalbogen Petra Moebus

Offer FEMLAB Software

Supporting Letters